CENTER FOR INTELLIGENT ROBOTIC SYSTEMS FOR SPACE EXPLORATION (CIRSSE)

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I. INTRODUCTION

This is the fourth report of the technical academic and professional activities of Rensselaer's Center for Intelligent Robotic Systems for Space Exploration (CIRSSE), a NASA University Center of Excellence which was established in June of 1988. In contrast to previous reports this one is produced as an annual publication covering the period between January and December 1990. The new format, approved last January, is more inclusive, compact and representative of the continuity of the activities of the calendar year.

The period covered by this report is the most productive of CIRSSE since its inception, and definitely reflects the efforts and accomplishments of the members of the Center and success of the team structure under which it operates. The key categories of the report are:

- Research Progress Report
- Faculty, Student, and Staff Recruitment
- Technology Transfer, Visits, Conferences, and Publications
- External Funding and Support
- Future Planning

Research on the main theme of Design of Intelligent Machines took a new dimension with the installation of the new ARONSON robot transporter incorporating two PUMA arms that form an eighteen degree of freedom kinematic chain for dual arm manipulation. This forms the basis of a dual arm testbed that also includes stereo vision; laser pointer, other sensory systems, and the necessary software to control the various subsystems. This effort provides an excellent medium to apply, test, and improve the theoretical results generated by the Center.

Specifically, the installation and hardware development of the ARONSON platform for the eighteen degrees of freedom manipulative system provides a unique environment for testing algorithms necessary to carry out space manipulation and assembly tasks. The VME bus attached to the system is used as the main carrier of data exchange between the hardware systems and the motion control system which is being developed and tested. This control software will be an excellent library for standard functions in such a dual arm system. The utilization of the multicamera vision system, with the Datacube presently used for object manipulative activities, is designed to provide interactive functions with the motion control system through elaborate software. The Petri-net coordination system is being developed to perform combined tasks under minimum supervision of an operator.

Mechanical grippers, designed for manipulation with the PUMA arms, are equipped with proximity and force sensors for precise manipulation and are integrated to the rest of the system. A tremendous effort, put forth during 1990, brought the hardware together and started the development of the software which will continue for the next year.

The mobile robot project got off the ground as a remote controlled navigation project through a maze of obstacles protected with ultrasound and infrared sensors. The addition of a camera will make its activities more autonomous and will provide precise information on collision avoidance, robot safety and will be useful for sensory integration.

Studies on flexible arms and plates, which have been funded mainly by sources outside of CIRSSE, is another research thrust to understand the behavior of large flexible structures in space.

Finally, research was continued in task planning, adaptive control of objects with unkown masses and robot control, reliability, and safety. The status of the individual projects is reported in Section II of this report.

The growth of the program at CIRSSE, reported in Section III of this report, shows very successful results. The size of our student population, both graduate and undergraduate has increased to 53 students, including six minority and eleven foreign students. The latter are supported through RPI funds. RPI undergraduate student retention was seven in the last semester. Dr. Steve Murphy, a graduate of CIRSSE, was also hired as a Post-Doctoral Research Associate to manage the testbed activities, raising the number of our staff to five.

Section IV of the report deals with the important subject of communication in the form of our technology transfer efforts to NASA, the American industry and the scientific community. During the year 1990, the CIRSSE research team made several visits to NASA research and field centers for exchange of information, and attended numerous conferences to make presentations of the research results generated by our Center. We also organized a very successful two-day conference at RPI, on November 29 and 30, 1990 where scientific papers were presented by both CIRSSE members and NASA researchers, and other world-wide known scientists and engineers. Two successful sessions were also organized at the SPIE Conference on Intelligent Robots in Boston, Massachusetts, November 5 and 6, 1990.

A large number of book chapters, journal articles, conference papers, and technical reports, published during the year 1990, are reported in the same section proving the continuation of the very strong intellectual activity of the CIRSSE team.

Section V reports the external funding activities of the Center and Section VI summarizes our efforts and discusses the Center activities planned for the next year. One of such activities is the planned cooperative efforts with JPL's Automated Systems Section, to look into the possibility of establishing a joint project on Remotely Supervised Autonomous Systems, where the CIRSSE testbed may be used for teleoperations in the CIRSSE program to meet NASA's needs for space exploration.

In summary, this was a very successful year for the Center where the implementation of various levels of the Intelligent Machine of the future started taking place.

GEORGE N. SARIDIS
DIRECTOR, CIRSSE

II. PROGRESS AND STATUS REPORTS

A. The Mathematical Theory of Intelligent Control

A COORDINATION THEORY FOR INTELLIGENT MACHINES

F.Y. Wang and G.N. Saridis

An Intelligent Machine is a Hierarchically Intelligent Control System composed of three levels: the Organization Level, the Coordination Level, and the Execution Level. An analytical model for the Coordination Level of Intelligent Machines has been developed as a step towards a realization of a mathematical theory for Intelligent Machines.

A framework for the Coordination Level with a tree structure consisting of a dispatcher as the root, and a set of coordinators as the subnodes, has been established. Petri net transducers have been introduced to model the dispatcher and coordinators. Coordination structures are defined as a formal model to describe analytically the coordination activities between the dispatcher and coordinators. Specifically, the coordination structure offers a formalism to:

- Describe the language (task plans) translation characteristics of the dispatcher and coordinators;
- Represent the individual process within the dispatcher and coordinators, especially their concurrence and conflict;
- Specify the cooperation and the connection between the dispatcher and coordinators;
- Perform the qualitative process analysis such as deadlock-free, boundedness, liveness, reversibility, etc., and the quantitative process analysis such as average execution time, system utilization, etc., for the whole Coordination Level;

- Provide a control and communication mechanism for the simulation and the real-time monitoring of the task process in the Coordination Level.

The process of decision making in the coordination structures has been identified as task scheduling and task translation. A scheduling procedure and an execution procedure for the task processing in coordination structures have been developed. Cooperative, Nash, and Stackelberg decision formulations with the corresponding learning policies have been proposed for the task translation in coordination structures. The learning process is measured with Entropy and the convergence of learning is guaranteed.

A case study for a prototype intelligent robotic system has been conducted. A coordination structure with one dispatcher and five coordinators has been built to model the robotic system. A simulation of the task processes has been performed and verifies the soundness of the theoretical results established.

PRIME: A Bottom-Up Approach for Rule Development

S. Miller and G.N. Saridis

PRIME is a system to be used by an intelligent machine to allow it to operate in an abstract but uncertain (or stochastic) environment. It maintains a model of the effects of the machine's actions in the form of a rule base, which is induced from experience. This bottom-up approach to rule development allows the model to adapt to changes in the environment.

Each rule consists of a condition under which the rule is active, an action, the effect of the action on the environment, and an estimate of the probability of this effect occurring. The effect probabilities are used to model the uncertainty in the environment, permitting multiple possible effects for a single action under a particular set of conditions.

The objective of the intelligent machine is to satisfy user-specified goals with maximum probability of success. PRIME fulfills this requirement in two ways: it continuously updates the rule base with the most recent information, to ensure the validity of the model; and it generates plans which have the maximum probability of achieving the goals, based on the probability estimates in the rule base.

PRIME is composed of three main processes: exploration, generalization, and planning. In exploration, the machine executes various randomly chosen actions, observes the effects on the environment, and updates the rule base accordingly. This process is used to develop the rule base in simulation, as well as, to supplement the current knowledge during normal operation. Generalization is the procedure used to induce general rules from experience, which is encoded in the form of specific rules. These general rules extend the machine's knowledge to situations which have not been encountered yet, thereby increasing the capability of the machine to plan effectively. Planning is the process of constructing an optimal sequence of actions to satisfy a goal, using the rule base to predict the effects of these actions and to determine the probability of success of the plan. The rule representation and many other data structures were specifically chosen to maximize the efficiency of these processes.

A simulated environment was designed to test the performance of PRIME.

PETRI-NET MODELING OF COORDINATION FOR THE DUAL ARM SYSTEM

M. Mittman and G.N. Saridis

The purpose of the project was to develop specification of coordination and communication among the coordinator level components of the CIRSSE dual arm testbed in a manner that allowed analysis of the plan. A program was developed to allow testing of the capacity of the CIRSSE system to pass the required commands. The following tasks have been completed at the present time:

- The X-windows graphical display has been developed for the Petri-nets which included making modifications to allow:
  - Colored tokens, and "tape" commands
  - Asynchronous screen updates
- Literature search was started for comparable systems
- Implemented the nets which were designed during the summer

The modifications necessary to allow asynchronous screen updates were completed. Since the net needs to run very slowly to allow people to watch it, the next step is to modify the program to allow the user to turn off the displays, and record relevant times. After that system load testing can be done.

The following tasks are needed in order to complete this project.

- run load testing,
- complete literature search, and
- analyze the structural properties of the designed nets.

State Space Reduction of Petri Net Models for Complex Interconnected Systems

H. Jungnitz and A.A. Desrochers

The research for CIRSSE has focused on the reduction of the state space of timed Petri net models used for performance analysis. The CIRSSE dual arm testbed is very complex, and the performance analysis is computationally expensive, due to the problem of state explosion. Our approach is to incorporate known results from queuing theory and use features from timed Petri nets and queuing networks (QNs).

Usually stochastic Petri nets (SPNs) for performance analysis are analyzed by solving the underlying continuous time Markov chain. For any model of reasonable size, such as the CIRSSE architecture, the state space grows very large, making the solution computationally hard or even impossible.

For a certain class of SPNs, it is possible to analyze subnets in isolation, and construct flow equivalent nets (FENs), which have the same temporal and input/output properties of the original net, but with a greatly reduced state space.

By using this technique, we can use a unified model, which can express the following characteristics in one representation, i.e., asynchronous operations, deadlock, and conflict. In addition, by using the techniques of flow equivalent nets, we can accomplish the performance analysis.

DISTRIBUTED CONTROL USING PETRI NETS

A. Bjanes and A. Desrochers

The architecture of a general purpose cell controller with decentralized control has been developed. In this control scheme, the actual system to be controlled is modeled using Generalized Stochastic Petri Nets. The controller structure and functionality is imbedded in the model of the system. The model is partitioned into several subnets, each of which represents some logical subsystem. This structure is an attempt to integrate these subsystems.

The model is then used directly to implement the controller for the system by generating run-time modules for each subnet. Each of these handles their respective parts of the system according to the partitioning of the global model, and communicates to the other controller using a globally shared data structure.

The controller can easily be reconfigured by changing the properties of the Petri net model of the system to be controlled.

The control system is implemented on UNIX workstations in C using TCP/IP communications protocol over Ethernet. X windows is used for the graphical interface. A host computer features the graphical user interface.

As transitions fire and tokens flow through the net, the display is updated continuously, allowing monitoring of the execution. The throughput of each transition is shown as well. Since the Petri net model is usually quite large, it is possible to select individual subnets (corresponding to the physical subsystems) to be displayed.

This software will be considered for implementation in the CIRSSE dual arm testbed.

Automated Step-by-Step State Reduction Method for Performance Analysis of Interconnected Systems

J. Kim and A.A. Desrochers

Systems such as the CIRSSE dual arm testbed are a connection of several subsystems. The control and performance analysis of the integrated system are important issues for effective operation. At the coordination level of the hierarchy, these systems are discrete event in nature. The integrated model for these systems has many discrete states, easily in excess of 1,000 or even 10,000.

This work proposes a state reduction method for the model when Petri nets are used as the modeling technique. A forward element of a subset is defined and this element is replaced by a simple place transition pair. It is shown that this replacement is legitimate if the complete element of the underlying forward element is structurally live. The replacement also introduces an approximation. The accuracy of this approximation is presently being evaluated.

Development of Petri Net Conversion Software

J. Peck and A.A. Desrochers

The purpose of this project was to develop software for the conversion of Petri nets between our different Petri net analysis packages. Each package offers different analysis capabilities, however, they do not include utilities for reading each others data files. Previously, nets were entered by hand for each package.

The utility GreatSPN2SPNP was created which converts Petri nets in GreatSPN format to that of SPNP. This allows the creation and analysis of the Petri nets in a graphical environment, with the ability to quickly transfer the net to SPNP for more advanced analysis. This utility has been placed in the CIRSSE archives, and is available to all for use with the Petri net packages.

The utility Great SPN2Silva converts Petri nets in GreatSPN format to that of the net reduction software on the VAX. Once again, the Petri net can be entered in the graphical environment of GreatSPN, and quickly transferred for further analysis.

Software has been developed which simulates the CIRSSE robotic system, using a Petri net transducer model. Further work involves a more efficient graphical interface, and a more refined model of the actual robotic system. This refined model should be expanded to include a telerobotic operator.

Skyline-Based Terrain Matching

L. Page and C.N. Shen

For autonomous navigation of an unmanned vehicle on a rough terrain such as the surface of Mars, two elevation maps are available: a rough, global map from aerial surveying of satellite observations, and a local measurement map observed with stereo cameras or a laser range-finder onboard the vehicle. The problem of terrain matching is to determine the relationship between the two maps; this relationship is expressed as the vantage, which is the position and orientation of the sensors with respect to the global map.

A new method was developed for performing the terrain matching, called skyline-based terrain matching. The orientation of the vantage is assumed known, but its translational parameters are determined by the algorithm.

Skylines, or occluding contours, can be extracted from the sensory measurements taken by an autonomous vehicle. They can also be modeled from the global map, given a vantage estimate to start from. The two sets of skylines, represented in cylindrical coordinates about either the true or the estimated vantage, are employed as "features" or reference objects common to both sources of information. The terrain matching problem is formulated in terms of finding a translation between the respective representations of the skylines, by approximating the two sets of skylines as identical features (curves) on the actual terrain. The search for this translation is based on selecting the longest of the minimum-distance vectors between corresponding curves from the two sets of data. In successive iterations of the algorithm, the approximation that the two sets of curves are identical becomes more accurate, and the vantage estimate continues to improve.

The algorithm has been tested on a simulated terrain.

A Connectionist/Symbolic Model for Planning Robotic Tasks

M. Moed and R.B. Kelley

This research develops an evaluation system, called the Associate Rule Memory (ARM), designed to operate with an interactive or automatic planner in a robotic-based world model. The ARM ranks alternative robotic actions based on the probability that the selected actions work as expected in achieving the desired effect. The system is experienced based and can predict the probability of achieving a desired effect for robotics actions for which it has no explicit past experience. The ARM is constructed to quickly and efficiently find high probability of effect robotic actions for a given desired effect.

The design of the ARM is a neural network called the Boltzmann Machine which is adapted for this work. An algorithm for training the ARM on robotic actions has been developed. The training algorithm is shown to converge globally to an accurate representation of the training set. Also, the network is able to develop hidden nodes that represent higher order relationships as part of the training procedure. The Genetic Algorithm (GA) is used for associative recall on the ARM. The GA is shown to be applicable to searching a Boltzmann Machine. A modified GA with an added immigration operator is shown to be more efficient on a test suite of functions. A proof is constructed to show that the GA with immigration is guaranteed to converge in probability to the optimum of a given function.

The use of the ARM as the Organization level of the Intelligent Machine of Saridis has been demonstrated. The functions of the ARM have been tested in the world of the NASA Flight Telerobotic Servicer.

Compliant Task Modeling

D. Sood and R.B. Kelley

Whenever a robot is asked to come in contact with another object, there is a collision. Typical tasks where the collision and contact must be controlled are the insertion of a robot-held object into a slot or hole, the installation of a printed circuit card, or the pushing/sliding of one object over another. In such cases, the situations can be modeled using traditional mechanical techniques. However, the purely kinematic approach requires that the mechanical parameters be known precisely. For this reason, it is of interest to consider a fuzzy control approach.

The purpose of this study is to determine ways to translate compliant tasks to a fuzzy control context. Once the task has been cast as a fuzzy control problem it is important to know the expected performance. To get a start on answering this question, a simulation is being developed to allow the comparison between the kinematic and fuzzy control approaches. This study will explore the performance changes as the values of the mechanical parameters depart from the assumed values to determine whether there is a cross-over point where the fuzzy controller's performance is better than the "perfect" knowledge controller. The stability of such fuzzy controllers is being studied in this context.

B. Multisensor Fusion

Hough Transforms for Visual Motion Detection

T. Tsolkas and G.N. Saridis

The problem of determining the position of an object in a structured environment using stereo vision, has been studied. A convex physical hull approximation is assumed for the description of the environment. A stereo pair of cameras with non parallel axes is used to track the object in the scene. Edges are extracted with the use of the Sobel gradient operator. Detection of the extracted edges is performed with a Hough transformation, that maps straight lines of the Cartesian space to points in the parameter space. Vertices are then extracted by calculating the intersections between the edges, and choosing those that correspond to real ones of the object. Finally, a stereo matching algorithm has been developed that matches the object's features (edges, vertices) extracted from the left and right view.

Restoration of Distorted Depth Maps Calculated from Stereo Sequences

K. Damour and H. Kaufman

Passive displacement and depth map determination has become an important part of vision processing. Applications include autonomous navigation, robotic assembly, and aerial cartography. With the reliance of such systems on visual characteristics only, a need to overcome image degradations, such as from motion and focus blurring and random image-capture noise, is clearly necessary. These image degradations can limit the accuracy and reliability of depth and displacement information extracted from such sequences.

To this effect, a model based Kalman estimator is being developed for spatio-temporal filtering of noise and other degradations in velocity and depth maps derived from image sequences or cinema. Two distinct cases are being considered; namely, the estimation of motion and depth for:

- general continuous fields, and
- scenes with several distinct rigid bodies of known shape and size.

Whereas the former is representative of the generating depth and/or velocity for an arbitrary field of view, the latter is relevant to an automated assembly situation.

In order to develop the depth and velocity field estimates, models are being developed for both the measurement process and the fields. Unlike previously developed procedures, the fields are being modeled both in the spatial and temporal domains with three dimensional autoregressive equations forced by a noise process. Measurements can be modeled in terms of the computed frame to frame intensity differences or in terms of directly estimated (say from region matching) values of the displacements. If the objects are of known shape and size, then this information can be used to improve the measurement model.

As an illustration of the proposed procedures, edge information from image sequences of rigid objects is being used in the processing of the velocity maps by selecting from a series of models for directional adaptive filtering. Adaptive filtering then allows for noise reduction while preserving sharpness in the velocity maps. Experiments will be conducted using several representative synthetic and real image sequences.

Frame-Rate Estimation of the 3D Pose of a Cylinder

K. Nicewarner and R.B. Kelley

A frame-rate method for 3D position and orientation (pose) estimation of a cylinder is being developed. When a camera is mounted on the gripper, this method provides frame-rate updates to the vision-guided servo that aligns the gripper relative to a cylinder to grasp the cylinder with minimal force or torque side effects. The method uses only a single image to estimate the 3D pose of the cylinder relative to the camera.

The method consists of scanning the image along two widely spaced bands in the image. These bands are processed to extract the high-contrast or critical edges. The four critical edges correspond to the edges of the cylinder in the image. From these four estimates, the 3D orientation of the cylinder is determined. The position of the cylinder is determined using the camera parameters, *a priori* knowledge of the diameter of the cylinder, and the four critical edges. The algorithm has been written, debugged and validated on a Sunstation. The algorithm is currently being implemented on the Datacube vision system to achieve frame-rate estimates. Experiments are continuing to obtain estimates of the expected errors and the robustness of the method to lighting variations. Extensions to other geometric shapes are anticipated.

3D Motion and Structure from Image Sequences

M. Repko and R.B. Kelley

The significance of this research is that it will allow physical phenomena of robot manipulators such as backlash, stiction, link flexibility and joint flexibility to be incorporated into dynamic modeling. These phenomena are often the cause of mechanical resonances and instabilities in the system, preventing the robot from accurately following a desired trajectory.

In the case of joint flexibilities, the position of the actuator, or the angle of the motor shaft, is not uniquely related to the position of the driven link. Control strategies that attempt to rectify this problem require link states such as position, velocity and acceleration. Unfortunately, these states are not generally available on commercial robots. It may be possible to obtain these 3D states by extracting them from a sequence of images. With the interest in light weight and flexible robot arms, the modeling and control of flexible beams has become more important. As with flexible joints, only partial state feedback is possible. Here is another case where 3D information can be used for full state feedback.

The relative motion between objects in a scene and a camera gives rise to apparent motion of the objects in a sequence of images. One method of characterizing this motion is to observe the apparent motion of a discrete set of brightness patterns in the image. Using only the local spatial and temporal derivatives of these brightness values, a dense 2D velocity map can be generated. This method is often referred to as optical flow. By including additional constraints, the 3D motion and structure parameters on the objects can be determined from the optical flow information. 2D image information is insufficient to determine 3D structure uniquely. In general, most techniques impose smooth motion and rigid body constraints on the physical world. The smooth motion constraint is not a drawback as long as the locations of discontinuities in the image motion field can be detected.

For the research at hand, the rigid body constraint will be relaxed. Specifically, the focus of the research is to recover the 3D motion and structure parameters for the cases when the rigid objects are connected by hinged, possibly flexible joints and when the object undergoes simple bending. An example of the first case is a rigid-link robotic manipulator with a heavy load. The second case arises with a flexible beam structure having simple bending modes.

Research has progressed to the point where the research problem is well-defined. A preliminary literature review has been completed. Several software simulations have been developed to validate the optical flow computations.

THREE-DIMENSIONAL VISION SENSING

J.R. Noseworthy and L.A. Gerhardt

During this last year, a well-focused program on three-dimensional sensing and application to a space environment was formulated. A multiple camera system was modeled so that on a simulated basis we could determine the effect of camera vibrations and placement on three-dimensional point estimation. An analysis was also started which compares different techniques used for three-dimensional point estimation including a least mean squared error technique and a mid-point between non-intersecting rays technique. An operating three-dimensional vision system using multiple cameras was developed and initial implementation was completed on the dual arm testbed. This system was demonstrated in November at the NASA Conference with the successful insertion of a strut into an existing set of nodes and struts as part of the automated assembly task, using visual feedback. This three-dimensional work is also being heavily integrated with the needs of other researchers on the program including Professor Sanderson for path planning, Professor Kaufman for depth maps, and Professor Kelley for assembly. Plans have been outlined for 1991 to include a full three-dimensional implementation with visual feedback for real-time visual servoing.

In more detail, with respect to the testbed project, the three-dimensional vision system was implemented using the Datacube which was purchased during this year.

The Datacube's VME chasis was customized to allow ethernet, serial, and parallel connections to the outside world. All necessary hardware modifications were completed, and the MaxWare software supplied with the Datacube was customized and ported to run on VxWorks. A custom hardware and software interface for the laser computer controlled laser scanner was developed so it could be controlled from the computer running VxWorks. All the hardware to mount the laser scanner as well as the two ceiling cameras was completed, and an additional two cameras were mounted on the PUMA robotic arm for additional stereo capability. All algorithms to perform the three-dimensional feedback task were written to be executed on the Datacube, including the Sobel edge detector, line thinning, thresholding, the Hough transform, centroid finding as well as camera calibration.

Three dimensional vision work is fundamental to the overall center activities and is strongly integrated with the work of other researchers.

C. Task Planning and Integration

ROBOT MOTION PLANNING FOR SPACE TRUSS ASSEMBLY

R. Munger and A.C. Sanderson

Planning algorithms for the path and trajectory of a strut during assembly of a space truss have been developed. The planning approach uses a discrete search over object configurations relative to a model of the partially completed truss. This discrete path provides the basis for a smooth motion path which is generated using potential functions. The resulting smooth path avoids collisions between the object and the truss, the strut and the truss, and the object and the robot. The approach provides an off-line plan which maps easily onto an on-line control using perturbations of the potential field to determine a final trajectory. This method has been used to define a path for the initial demonstrations of truss assembly in the CIRSSE dual arm testbed, and will be explored for application in programs at NASA Langley.

REASONING ABOUT GEOMETRIC CONSTRAINTS FOR ASSEMBLY SEQUENCE PLANNING

S.S. Krishnan and A.C. Sanderson

Assembly sequence planning can be decomposed into feasibility analysis of the cutsets of the graph of connections among parts leading to the generation of the AND/OR graph representation of the resulting sequences. This analysis requires reasoning about the feasibility of part motions subject to geometric constraints from other parts, subassemblies, fixtures, and manipulation devices.

In this work, geometric reasoning for these problems is based on the introduction of an algebra of polyhedral cones which provides a tool for combining geometric constraints from different part relations. In the multistage case, the feasibility of successive polyhedral cone paths defines a multistage optimization problem, and avoids the explicit generation of a configuration space representation. A simulated annealing algorithm applied to a multiresolution tree in the motion space is introduced as a means to efficiently evaluate feasibility and select desirable paths. This approach identifies free space regions and avoids local minima through probabilistic annealing of both the representation tree and the constraint cost function. The algorithm generalizes to multistage translation-rotation sequences which, in the limiting case, would encompass all possible motions.

A Hierarchical Planner for Space Truss Assembly

R.K. Mathur and A. Sanderson

Construction, repair, and maintenance of large, complex space-based structures will require extensive planning of operations in order to effectively and reliably carry out these tasks. This thesis has presented a hierarchical planning paradigm focusing on space truss assemblies. This planning paradigm produces sequences of assembly operations which might be used for human, tele-operator, or autonomous robotic implementation. Emphasis is placed on the generation of valid sub-goals which satisfy geometric (accessibility) and structural (rigidity) constraints. A hierarchical state representation has been used to develop sub-goals, and special cost-functions guide the search for locally optimal sequences. Results from the implementation of the planner are presented for two case study assemblies with up to 31 nodes and 102 struts.

Path Planning Using the Recursive Compensation Algorithm

C.H. Chung and G.N. Saridis

In path-planning algorithms, attempts are made to optimize the path between the start and the goal in terms of *Euclidean* distance. Since the moving object is shrunk to a point in the configuration space, the *Findpath problem* can be formulated as a graph-searching problem. This is known as the *VGraph Algorithm.*

The drawbacks of the *VGraph Algorithm* have been identified. The main drawback is related with rotation of a moving object. This drawback has been resolved by using the *approximation method.* However, the *VGraph Algorithm* has serious drawbacks when the obstacles are three-dimensional. The *Recursive Compensation Algorithm* has been proposed to solve the drawbacks of the *VGraph Algorithm*. The *Recursive Compensation Algorithm* has to find the collision-free shortest path in 3D without increasing the complexity of the *VGraph* and it is proved to guarantee the convergence to the shortest path in 3D. Simplifying the *VGraph*, the *Recursive Compensation Algorithm* can save not only the memory space to represent the *VGraph* but also the graph-searching time. The *Recursive Compensation Algorithm* suggests how to calculate the optimal size of the additional nodes along the edges for the shortest path. Finally, the global optimal path can be analytically computed by using the *Recursive Compensation Algorithm.*

A SUPERVISORY CONTROL STRATEGY FOR NAVIGATION OF MOBILE ROBOTS

K.J. Kyriakopoulos and G.N. Saridis

Collision avoidance for a mobile robot in an environment of moving obstacles has been examined. The problem is decomposed into:

- collision prediction
- collision avoidance

The sensing model is integrated into the collision prediction scheme. The collision avoidance strategy uses the dynamic model of the mobile robot.

A Kant-Zucker path decomposition is adopted and three strategies have been developed:

- Minimum Interference Strategy (MIS)
- Optimal Control Strategy (OCS)

- Potential Fields Strategy (PFS)

Furthermore, a comparative study of these methods in terms of:

- Optimality
- Computational Complexity
- Update Efficiency

was done.

Simulation results have been obtained for all three strategies.

Two Arm Manipulation/Path Planning

F. Schima, J. Weaver, and S. Derby

The two arm robot path planning problem has been analyzed and reduced into components to be simplified. This project examines one component in which two PUMA-560 robot arms are simultaneously holding a single object. The problem is to find a path between two points around obstacles which is relatively fast and minimizes the distance.

The project involves creating a structure on which to form an advanced path planning algorithm which could ideally find the optimum path. An actual path planning method is implemented which is simple though effective in most common situations. Given the limits of computer technology, a "good" path is currently found.

Objects in the workspace are modeled with polytopes. These are used because they can be used for rapid collision detection and still provide a representation which is adequate for path planning. The project has been structured to be modular in nature for the other modes of two arm robot operation. These include two arm path planning for independent motion and dynamic obstacles.

Collision Detection

G.J. Hamlin, J. Tornero, and R.B. Kelley

A collision detection and distance calculation algorithm has been developed and implemented. This algorithm uses a spherical-object geometry that approximates objects by an infinite number of spheres. The shortest distance between two objects in this geometry is obtained by finding the two spheres, one in each object, that are closest. The distance is then calculated along the line joining the centers of the two spheres.

Excellent numerical results have been obtained. For example, self-collision checking for a PUMA robot arm is computed in less than 3ms; advantage is taken of *a priori* knowledge of the kinematics of the arm, such as knowing which links can never collide. Self-collision checking for the dual robot-arm CIRSSE dual arm testbed can be computed in 220 ms, or less than 40 ms if a less precise representation is used.

Currently, work on implementing on-line collision prevention is underway. A model of the forward kinematics of the CIRSSE testbed is being integrated with the collision detection algorithm. This "watchdog" system will prevent both human operators or computer controllers from causing collisions among the testbed elements.

D. Multi-Arm Manipulation

MULTIPLE COOPERATING MANIPULATORS ON A MOBILE PLATFORM

S.H. Murphy and G.N. Saridis

This work examines the problem of modeling and simulation of multiple cooperating manipulators on a mobile platform. The system of cooperating robot manipulators forms a closed kinematic chain where the forces of interaction must be included in the formulation of robot and platform dynamics. The formulation includes the full dynamic interactions from arms-to-platform and arm-tip to arm-tip and the possible translation and rotation of the platform. The structure of the closed chain dynamics allows the use of any solution for the open topological tree of base and manipulator links. A simulation of two cooperating manipulators on a mobile platform is presented and the motion is graphically displayed. Additional dynamic model accuracy is achieved through the development of Newton-Euler modeling techniques for geared manipulators and manipulators with non-negligible joint flexibility. The resulting Newton-Euler models of flexibly jointed manipulators and geared manipulators have many advantages over the traditional Lagrange-Euler methods; the complete effects of the gear ratios and the gyroscopic effects of the spinning motor/gear are included in the recursive formulation, and the number of computations in the simulation of flexibly jointed and geared manipulators grows linearly with the number of links. Additionally, any function for the flexibility between the motor and link may be used, permitting the simulation of nonlinear effects, such as backlash, in a uniform manner for all joints. The detailed structure available in the model is used to examine linearizing controllers and show the dependency of the control on the choice of flexible model and structure of the manipulator. The geared modeling techniques are applied to the dynamics of the geared PUMA manipulator and are used to show the significance of motor gyroscopic forces on manipulation on a mobile platform.

A Model for an 8-dof Manipulator: Kinematics

L. Carmichael and G.N. Saridis

The work done as of today can be placed under the headings of Dynamics and Kinematics.

Dynamics

The simulation code for the PUMA dynamics was updated in order to be able to handle an nth dof manipulator with prismatic joints.

Some preliminary values for the dynamic parameters of mass and inertia for the platform were calculated analytically.

Kinematics

A kinematic model for the PUMA/Platform was developed. In this model, the PUMA and Platform were linked and treated as one manipulator with nine joints and nine coordinate frames. Also, the Jacobian for the nth dof manipulator was calculated.

Several algorithms for the calculation of the inverse kinematics were analyzed and implemented. An algorithm utilizing the Jacobian pseudo-inverse was tested and found to be computationally inefficient. The Extended Jacobian was also found to be computationally inefficient. An iterative solution to the inverse kinematics had convergence problems around singular points.

An analytical solution to the inverse kinematics was developed. In this solution, two redundant variables were introduced into Cartesian space. These variables determined the configuration of the manipulator. Since the nine dof manipulator can be considered to be an eight dof manipulator with a mobile base, there exists a one to one mapping between the joint space and Cartesian space. This analytical solution was displayed for the demo via simulations on Silma.

The forward kinematics mapping the joint angles to the Cartesian position and orientation and the redundant configuration variables was developed.

Development of a Control System for a Pair of Robotic Platforms

J. Cosentino and A. Desrochers

The robotic transporter has been successfully interfaced to the CIRSSE Sun system. Software has also been implemented, tested, and demonstrated.

A platform library was developed to coordinate and organize the low-level drivers. Joint level controllers for the platforms, imbedding characterization of the platform dynamics, were designed. Finally, a software test pendant was implemented which uses path planning to facilitate smooth joint positioning based on user input, and demonstrates the effectiveness and usefulness of the entire control system.

This project served as the basis for inclusion of the platforms into a larger robotic system. The software developed allows easy access to the platforms, and provides an organized foundation upon which future projects can build. The determination of the platforms' dynamic parameters will also aid in future controller design.

Robot Force Control in Multiple-Arm Manipulation and Contact Tasks

S. Murphy, L. Wilfinger, and J. Wen

Enhanced understanding of the control and robustness issues related to robot force control has been obtained in the past year.

It was recently pointed out that in the force control of robot arms, either in contact tasks or multiple arm manipulation, orthogonal decomposition may result in unit inconsistency due to the mixing of units for force and torque. By decomposing the force directly in the task frame, the unit inconsistency is avoided, and the advantage of orthogonal decomposition is still preserved in that the force and motion control loops can be separately designed.

In the stability analysis for the force loop, it has been found that direct force feedback is not robust with respect to the time delay but can be remedied with an integral force feedback. However, the integral force feedback is itself sensitive to unmodeled environmental flexibility. More specifically, the product of the integral feedback gain and environmental stiffness should be sufficiently small to ensure stability. This result was also observed experimentally.

Currently, research is focusing on tuning the feedback gain based on environmental stiffness adaptively.

Flexible Arm Research

F. Wang, D. Hughes, R. Buche, and J. Wen

Major progress was made in the past year in terms of modeling, control, and development of an experimental testbed in the flexible arm research.

A systematic development of the nonlinear equation of motion for a single link flexible arm has been developed based only on two assumptions: 1) no independent elongation, and 2) Hooke's Law holds between stress and strain. This equation is then linearized by assuming small bending and velocities. The resulting equation is one of the first *correct* linearized equation for flexible beams. The linearized partial differential equation can be discretized exactly through a decomposition using natural modes. Excellent agreement (within 5%) between experimental and analytical modal frequencies is obtained.

The mode shapes based on the linearized equation are then used to discretize the nonlinear equation, and the resulting equation satisfies an important passivity criterion. This passivity property implies that a large family of stabilizing feedback compensators can be used. The structure of the control laws in this family is a low gain proportional and derivative feedback in parallel with a passive (positive real) compensator with the motor velocity as the input. By emphasizing the compensator gain at the natural frequencies of the beam, improved step response is obtained. This procedure can also be extended to flexibly jointed robots.

Continuing research will focus on a systematic procedure of tuning the positive real compensator for the optimal performance, and the extension to tracking control and adaptive control.

E. Adaptive and Learning Control

DIRECT MODEL REFERENCE ADAPTIVE CONTROL OF ROBOTIC MANIPULATORS

R. Steinvorth and H. Kaufman

Direct adaptation offers the potential for uniform control of robotic manipulators in the presence of uncertain flexibilities, changing dynamics due to unknown and varying payloads, and nonlinear joint interactions, without explicit identification.

Adaptive control methods provide a systematic solution to regulation problems which contain process and/or environmental uncertainties. The distinction as to whether an adaptive algorithm is an indirect or direct method represents the most general classifying feature of different adaptive methods. Indirect control methods utilize separate parameter identification and control schemes. Thus, these methods rely on explicit identification of plant parameters which the algorithm in turn uses to determine the control value. In contrast, direct adaptive control methods merge the identification and control functions into one scheme. These methods adjust controller parameters directly, using only plant input and output signals.

Of particular interest for robot control is a direct model reference adaptive control (MRAC) algorithm previously developed at Rensselaer, based on command generator tracker theory. The appealing characteristics of this adaptive control algorithm over indirect methods and other direct reference methods include:

- lack of dependence on plant parameter estimates,
- direct applicability to multiple input-multiple output plants,
- sufficiency conditions which are independent of plant dimensions,

- control calculation which does not require adaptive observers or the need for full state feedback,

and

- ease of implementation.

One major drawback to this method has, however, been the need for the process to satisfy a positive real condition. This condition has now been alleviated by a new modification which incorporates a time varying linear filter operating on the error between plant and model output.

This result is a major contribution since it enables the application of direct MRAC with asymptotic tracking to a highly expanded set of multiple input-multiple output processes.

Simulation results using a nonlinear model of a flexible joint arm in the presence of sudden load changes show that the developed modifications for MRAC do indeed result in satisfactory model following without knowledge of the load change values and without apriori information about the flexibility.

Furthermore, application of the MRAC to the nonlinear coupled dynamics for a 2 link PUMA manipulator, again in the presence of sudden load changes, show that each joint angle closely tracks a desired cycloidal trajectory. Presently the MRAC is being applied to a more extensive simulation of the PUMA system.

EXPERT AIDED ADAPTIVE CONTROL

G. Sullivan and L.K. Lauderbaugh

The purpose of the expert aided adaptive controller, (A/E controller), is to diagnose problems in the identification and control algorithms used by an adaptive controller, and then formulate plans of corrective actions.

Overview

The A/E controller consists of four main pieces; an adaptive controller, the signal-to-symbol interface, the symbol-to-procedure interface and the expert system module. The signal-to-symbol interface gathers data from the adaptive controller over a constant time period called the expert system sampling interval and converts this data to a format that the expert system module can use. At the end of each expert system sampling interval, the Expert System Module polls the signal-to-symbol interface and receives a description of the state of the adaptive controller. Using the information in its knowledge base, the expert system module diagnoses problems with the adaptive controller and then formulates a schedule containing the names of procedures used for further diagnosis, or for the enhancement of the adaptive controller's performance. The last step in the A/E controller cycle is performed by the signal-to-procedure interface, which activates the procedures on the schedule as their starting times arrive.

During the past six months, three main activities have taken place to bring about the conclusion of the A/E controller project:

- development of signal processing and analysis algorithms used for diagnosis and treatment,
- development of a simulation facility to test the A/E controller,

- finalization of the adaptive control knowledge engineering and it's implementation in the IPEX expert system shell.

After completing the work in these three areas this fall, test cases were run to exercise the expert system's response to a wide range of problems that are encountered in adaptive control applications. Results of the tests were promising and show that expert system supervision can significantly extend the domain of operating conditions over which adaptive controllers work well.

F. Reliability and Safety

RELIABLE CONTROL AND SENSOR FUSION IN INTELLIGENT MACHINES

J.E. McInroy and G.N. Saridis

Although robotics research has produced a wealth of sophisticated control and sensing algorithms, very little research has been aimed at reliably combining these control and sensing strategies so that a specific task can be executed. This work uses a probabilistic approach to improve the reliability of intelligent machines.

The designer, which may be a human in the case of telerobotics or the Organizer in an intelligent machine, must first provide a set of plans, $A=\{A_1,\ldots,A_n\}$. Because only explicit tasks are considered (i.e., "measure object position and grasp") the plans will consist of nothing more than a set of control and sensing algorithms appropriate for the task. In addition to the plans, the designer must also provide a set of specifications, S_D, which must be satisfied for the task to be termed a success.

A two stage technique is proposed to select the reliable plans. First, Jaynes Maximum Entropy Method is used to generate a set of entropy inequalities which must be satisfied to ensure reliable operation. The entropy formulation has several advantages. Especially advantageous in modern distributed robotic systems is the invariance of entropy with respect to homogeneous coordinate transforms, which allows entropies measured in different homogeneous coordinate frames to be easily fused. By using the entropy based elimination algorithm, a large number of unsuitable plans can quickly be excluded from further analysis. The remaining plans are termed *feasible plans*.

The second stage of analysis makes use of reliability analysis techniques to calculate the probability of success of each feasible plan. Depending upon the *a priori* statistical information available, either maximum likelihood estimation or the first order, second moment methods of structural engineering may be used for calculating the reliability in meeting each specification. These reliabilities can then be combined to find the probability of meeting all of the specifications simultaneously.

To validate these concepts, a case study analyzing visual positioning has been developed. The accuracy in positioning in the presence of both forward and inverse kinematic errors as well as pixel truncation is stochastically modeled. The model clearly shows the connection between accuracy and range, so higher accuracy measurements can be obtained by moving the cameras closer (at the cost of increased time). Since the improvement can be analytically assessed, the trade-off can be mathematically evaluated.

Safety in Control Systems

V. Ree and L.K. Lauderbaugh

The goal of this project is to find a method of incorporating safety directly into control problems. The method being investigated is based on an optimal control formulation. In this method, the minimization of risk to the system from hazards is one objective of a multiple objective optimal control problem. The other objectives in the problem are those describing the performance of the system in accomplishing its task.

In measuring the risk from hazards to the system, each hazardous event has a risk defined as the product of the occurrence of the hazardous event and the utility loss due to the occurrence of that event. Utility, a term borrowed from decision theory, is a measure of satisfaction derived from the occurrence of events. Essentially, utilities are used as measures of the relative weights of the hazardous events.

In assessing the probability of the occurrence of a hazardous event, the assumption is made that all hazardous events are mathematically describable as regions in state-space. Therefore, given the probability distributions describing the state-variables, it is possible to describe the probability of the occurrence of the hazardous event. Determining these probability distributions of the state-variables given state trajectories is a matter of further research.

Another assumption that is made with respect to risk to the system is that, the hazardous events that are considered are linear in their utilities. If there are N hazardous events, each with a utility u_i, i=1...N, then the total risk to the system is the sum of the individual risks from each event. The reason this assumption is made is that if all possible combinations of the N events occurs, the total number of hazardous events that would have to be considered would be 2^N-1. Such events which are linear in their utilities are termed "Top Events".

For the experimentation phase of the research, a problem in collision avoidance between a mobile robot and obstacles was considered a benchmark problem for the work in safety. During the past year, work progressed on establishing CIRSSE's Mobile Robot Facility. This facility will form the testbed for experimentation.

G. Parallel Computation and Information Management

3D Sensing and Testbed Integration

A. Ryan and L. Gerhardt

Art joined CIRSSE in August 1990 and was self supported in the Fall of 1990. He spent most of September acquainting himself with the ongoing vision research and the lab's computer system. In late September and early October, he worked with Russ Noseworthy calibrating the ceiling cameras for the testbed.

In late October he wrote a program to manipulate the pattern files we use to generate structured light on the laser scanner. This program takes a pattern file and will translate and scale the pattern coordinates in the X and Y axes, and rotate them about the laser's origin point. This program gives us the capability to modify our pattern files without having to completely re-write them.

In November he started working on the "laser servoing", which is the process of directing the laser to move to a desired point in the ceiling camera's field of view.

This program acquires an image from the camera and locates the centroid of the laser spot. If the laser spot is not at the desired pixel location, the laser is instructed to move the spot a certain distance and the centroid of the laser spot is calculated again. This process continues until the laser spot is detected at the desired location. This program will give us the capability to use the laser as a pointing device and give us a means of calibrating the laser scanner. This program was shown in the laboratory demonstrations during the CIRSSE NASA Conference in November.

Attributed Image Matching Using a Minimum Representation Size Criterion

B. Ravichandran and A.C. Sanderson

The interpretation of complex sensory data is fundamental to a variety of applications domains, and the matching of stored model structures to observed data from one or more sensors is an important approach to this problem. The minimum representation criterion is a metric of the overall complexity of a model and facilitates the unsupervised identification of model structure as well as parameters. This report describes the use of this approach to the problem of matching noisy gray-level images to attributed models. Using the minimum representation criterion, the match between gray-level image features and an attributed graph model incorporates a representation size measure for the modeled points, the data residuals, and the unmodeled points. This structural representation identifies correspondence between a subset of data points and a subset of model points in a manner which minimizes the complexity of the resulting model. The minimum representation matching algorithm described in this work is polynomial in complexity, and exhibits robust matching performance on examples where less than 30% of the features are reliable. The minimum representation principle is being extended to three-dimensional models and multisensor data matching. A simulated annealing algorithm is being developed to improve the efficiency of this method, and parallel implementation on a Boltzmann machine architecture has been designed. These matching methods will be tested on image data from NASA Langley for usual servo alignment of struts and nodes in truss assembly using robot-mounted cameras.

H. Experimental Facilities

TESTBED PROJECT PROGRESS REPORT

K. Walter

Testbed

The testbed hardware provides CIRSSE with a facility where experimentation and integration of the various research projects will take place. This facility consists of the Computer Systems, Real-Time Control System, Vision Systems, and the Robot Transporter Platform, as well as the PUMA robots. Each of these subsystems will be discussed in detail. Please refer to the CIRSSE NASA Lab Configuration diagram included at the end of this section in Figure (1).

Computer Systems

The various computer systems at CIRSSE provide a distributed computing environment which is networked via TCP/IP Ethernet. Access to the worldwide

Internet is available through the campus gateways. The systems and their main functions are detailed below.

- SUN 4/260
  -- File/Compute/Terminal Server to CIRSSE local network
  -- Gateway to RPI campus network
  -- Local X client

- SUN 3/260C
  -- Host to MATROX vision system
  -- Host to TAAC applications accelerator
  -- Host to DATACUBE image processing system
  -- Local X client

- SUN 3/150
  -- Program development workstation
  -- Local X client

- SUN 3/60C
  -- Program development workstation

- SUN 4/60
  -- Host to Real-Time Control System

Equipment is currently on order to enhance the performance of the 3/150 by upgrading to a 4/350. This will increse the performance of this machine from 2 to 16 MIPS. An additional 8 MB of memory will also be added and this machine will then be able to perform the compute server tasks for the local net. We are also planning to enhance the file server by upgrading to a faster disk controller and adding an additional 8MB of memory. These enhancements will provide noticeably faster performance of the local net.

Over the last year we have added X window support to the computing environment. This has enabled us to purchase seven X-terminals which are physically distributed among the CIRSSE laboratories and offices. These terminals have afforded all CIRSSE personnel with better access to the high-resolution graphical displays that are required by the applications and development software.

Real-Time Control System

During the past year the Real-Time Control System has undergone major additions and enhancements. Please refer to the Real-Time Control System diagram located at the end of this section in Figure 2. The system is currently running VxWorks Version 5.0 on five MVME-135 68020 processors. Other cards and their functions are:

1	MVME-330 ethernet controller
1	MVME-224 4 MB shared memory
2	VME-7016 Qbus converter, for direct control of the Unimation controllers
1	MVME-340A parallel I/O, force/torque sensor communication
1	MVME-332XT 8 channel serial I/O, gripper controller communication
1	DVME-628V 8 channel D/A for driving the 6 axis platform
1	VMIVME-2532A HVDIO to interface with the 12V I/O signals to the platform controller
3	VME-3570 interfaces for the incremental encoders on the platform
1	XVME-566 16 channel A/D converter for analog sensors

All of the hardware has been integrated to provide full platform and PUMA control. VxWorks drivers have been developed for all of the above cards and work has been ongoing to bring up a working version of the KALI motion control software from McGill University. In addition to the hardware integration that was necessary to interconnect with the transporter platform, all of the emergency stop signals from the PUMA controllers and the robot transporter are interlocked. Remote E-stop switches have also been added to increase the safety factor of operating the 18 DOF system.

Vision Systems

A Datacube image processing system has been added to the network which enables frame rate processing of acquired images. Three ultra-minature cameras have also been added which makes a total of five cameras available for image acquisition. The Datacube can access any two of the five cameras simultaneously. A camera pair for stereo imaging is mounted on the ceiling overlooking the workspace, another camera pair is mounted at the wrist joint of one of the PUMA arms, and the fifth camera is mounted on the wrist joint of the other PUMA.

The Datacube is hosted by a local MVME-147 68030 processor which has an embedded ethernet controller that connects to the local net. Each of the two frame grabber boards can support 8 monochrome or two color cameras. This capacity can be increased by adding additional frame grabber boards. The MVME-135 68020 processor that controls the laser scanner also resides in the Datacube.

The laser scanner is mounted on the ceiling near the two cameras overlooking the workspace. This device is used as a pointer that can highlight a target for the vision system, or for generating structured light over a target area to enable the system to extract 3D information. All of this equipment has been in place for less than a year, and tremendous progress has been made in integrating the hardware and software development.

Robot Transporter Platform

The Robot Transporter Platform was delivered by K.N. Aronson in April 1990. It has been fully integrated with the control system and software support is currently being developed. A raised floor has also been installed around the platform which not only conceals the vast amount of cabling that is required, but also enables the robot arms to pick an object from the floor surface. Future work with this facility will consist of developing a robust software control package as well as implementing a calibration scheme.

PUMA Robot Arms

Custom grippers designed by CIRSSE have been built and mounted on both PUMA arms. These grippers are lightweight and fully instrumented. Each gripper contains a cross-fire sensor, force sensing fingers, and finger position sensors. The gripper assembly is mounted on the force/torque sensor and controlled by a 68HC11 based controller that was also designed within CIRSSE. The gripping force is variable and controlled by a pneumatic servo. All communications between the gripper controller and the Real-Time Control System are via a serial line. Additional cabling was installed internal to the PUMA to support the gripper.

NASA Lab Configuration

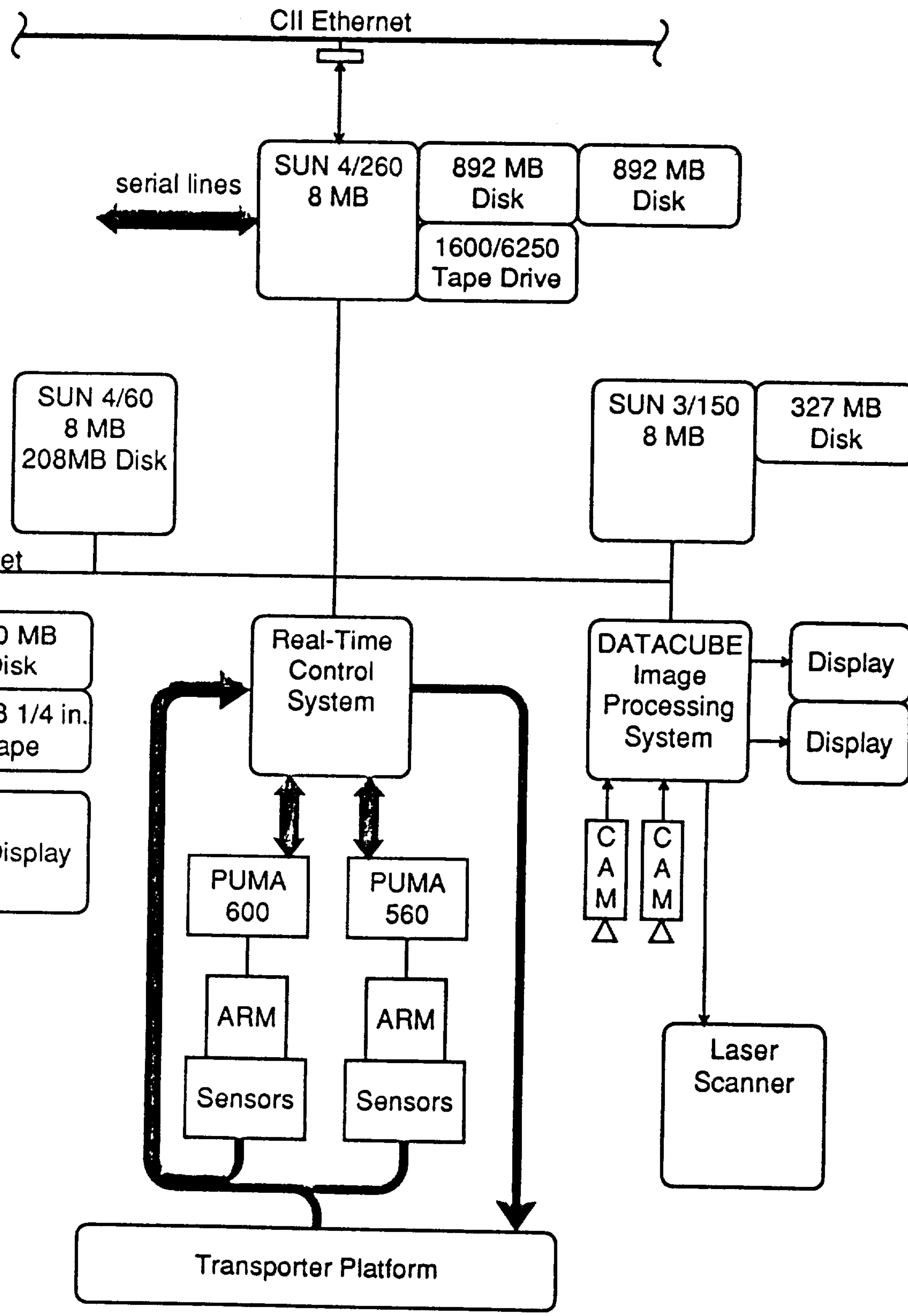


Figure 1

REAL-TIME CONTROL SYSTEM

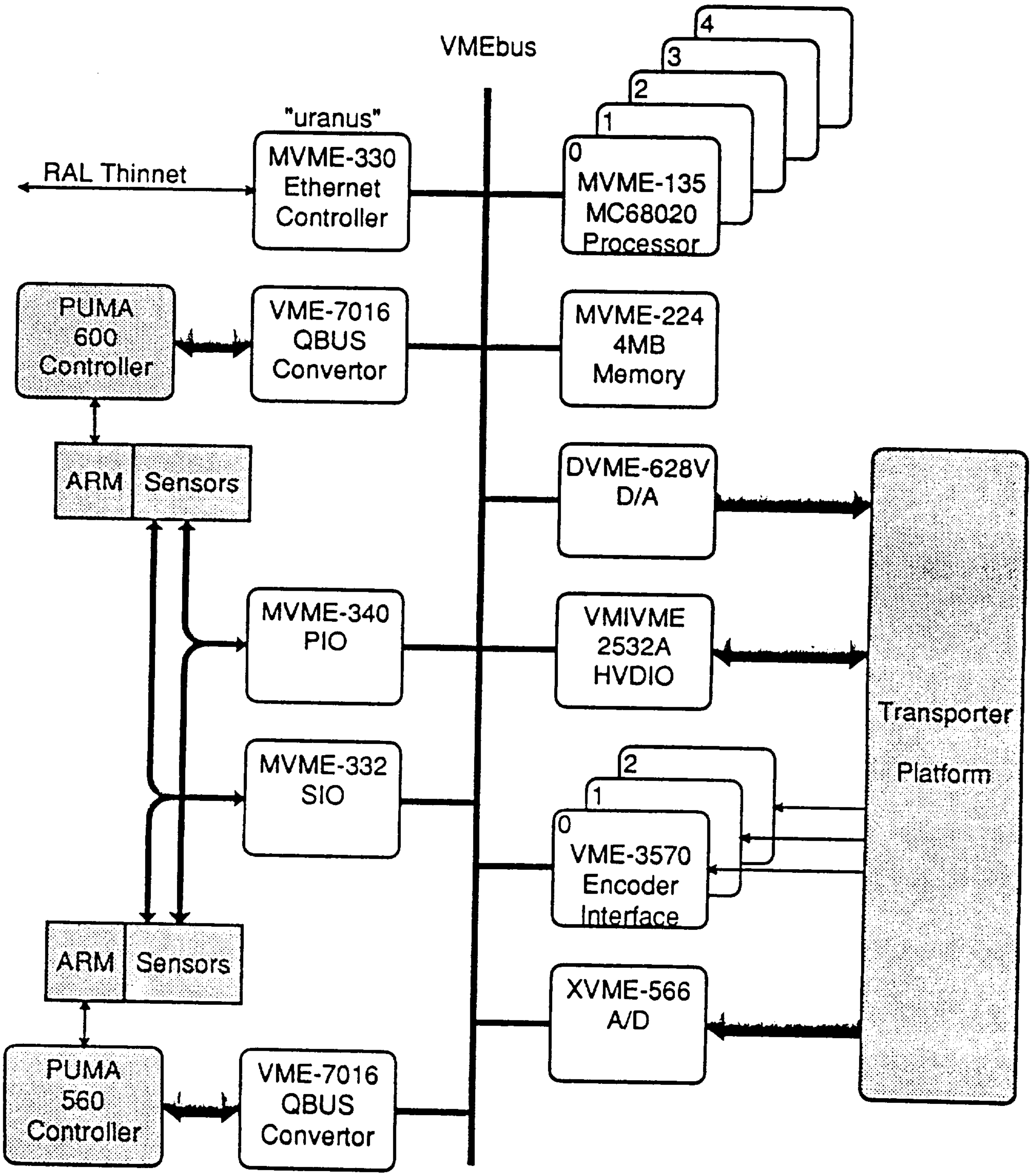


Figure 2

CIRSSE MOBILE ROBOT FACILITY

P.A.L. Silverthorne, A. Behar, M. Ryan and L.K. Lauderbaugh

During the past year, work progressed on the development of the CIRSSE Mobile Robot Facility. The purpose of the facility is to provide a testbed for experiments involving mobile robotics.

Currently, the facility has a TRC Labmate Mobile Robot Platform. The robot's sensor system includes eight ultrasonic and eight infrared sensors. The robot is controlled using a host computer system, presently a 386-PC with serial communication between robot and host.

Recent and proposed improvements for the facility include a telemetry system, with a radio link between robot and host; additional sensors, more powerful host and on-board computer systems, and a tracking system to ensure accurate positioning and navigation.

In addition to the hardware improvements, the robot control software is being redeveloped and augmented for a more hierarchical structure. In this software structure, code, written in C, is divided into several levels. C functions and routines at any level are composed of functions that are defined in lower levels. However, at the lowest level reside the basic functions which control the robot's motors, sensors, and communication interfacing.

The goal of the facility's development is to furnish a platform which can be intelligently controlled for various experimentation programs. Some of the programs include safety, mobile vision, intelligent sensing and control, unstructured collision avoidance, and an additional vision platform for the two-arm testbed project.

ROBOTIC GRIPPER MECHANICAL DESIGN

J. Peiffer and S. Derby

A redesign of the current single pneumatic servo gripper so as to better function in the CIRSSE role was performed. The new grippers must be able to manipulate the current NASA strut member, as well as other similar items that will need to be manipulated in the future for CIRSSE.

The design work was able to reduce the weight by 25%, reduce the length by 20% and design around a commercially available air cylinder. This improved overall performance, and kept critical parts available. Also designed were several other grasping linkage options with the same base if the gripping action needs to be parallel rather than rotational.

Three identical grippers were fabricated and have been supplied to the NASA CIRSSE labs. These were designed to be placed on the two PUMA robots on the robot transporter. They are designed to also function for other future research projects. The third gripper gives a source of replacement parts, and the ability to try new modifications without hindering other researcher's work.

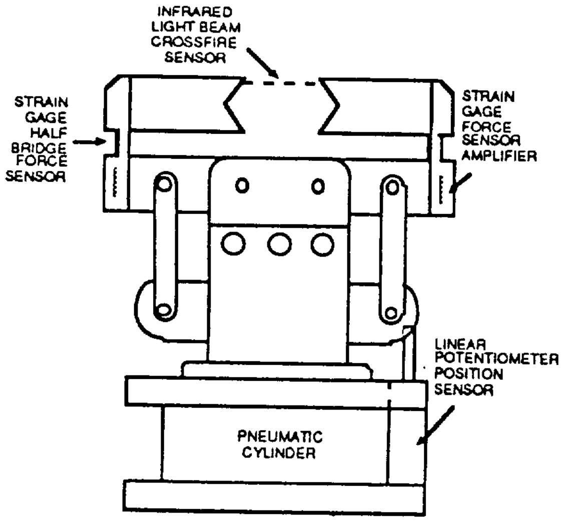
CIRSSE GRIPPER CONTROL

J. Peiffer, S. Derby, J. Tsai, J. Bethel, and R.B. Kelley

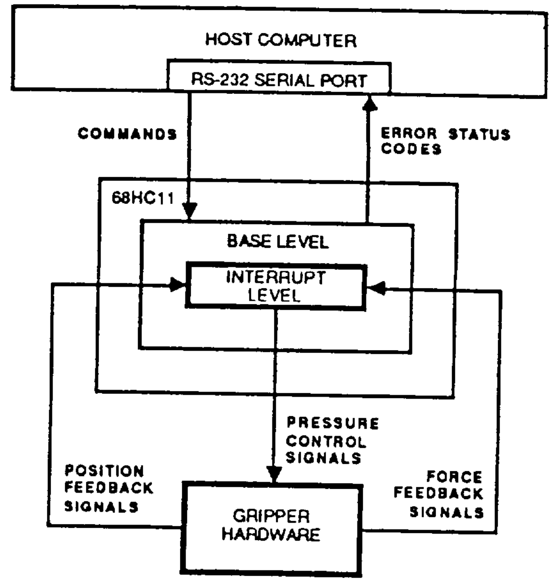
The major design features of the CIRSSE gripper are a reduced length (14cm, base to fingertip), weight (0.8 kg) and the associated wrist force-torque sensor mounted moment arm (21 cm); a pneumatic servoed grasping force-to-weight ratio greater than 25-to-1; dedicated slave controller using the MC68HC11 8-bit micro-controller; real-time interrupt driven control; remote tuning of position and force servo parameters by the host computer; a simplified host-gripper communications protocol; and integral self-check, calibration, and controller confidence routines.

The CIRSSE custom designed double sided gripper interface board provides regulated power for the sensors; the pneumatic valve drive electronics; the drive for the fingertip crossfire sensor; and signal conditioning for the position, force, and crossfire sensors.

On power-on, the controller performs a hardware self check and starts the gripper control in position servo mode to prevent gripper motion. A simple real-time executive is implemented that servos either to a software selectable position or force set point. The executive permits the dynamic tuning of the control law parameters while servoing. The controller communicates with the host over an RS-232 serial line. (Note that any host with an RS-232 serial port may be used to control the gripper.) The software is integrated into CIRSSE's VxWorks real time control environment.



Sketch of the CIRSSE Gripper.



CIRSSE gripper controller architecture.

Strut Connector and Node Design and Construction

K. Nicewarner and R.B. Kelley

Using the NASA Langley supplied strut as a model, a simplified strut connector and node was designed. The design of the self-locking connectors was based on simplicity and ease of construction. A prototype was first built and tested to prove the concept and to improve the eventual design. Twelve connectors and six nodes were constructed of aluminum and six struts were fabricated from steel conduit. This provides the capability to construct a tetrahedral truss structure.

The availability of this simplified truss structure hardware helped to expedite the development of sensing and manipulation software. The strut length is scaled to approximately 75 cm (vs. 2m). The connectors provide similar functional demands on the assembly of the struts into truss structures as the NASA model. (However, the simplified connectors are not easily disassembled by a single robot.)

CALIBRATION OF THE CIRSSE TESTBED MOBILE PLATFORMS

A. Lin and R.B. Kelley

Each mobile platform has three elements: a linear transport carriage and two rotational elements which provide pan and tilt motion. These elements are equipped with incremental encoders. On power-on, it is necessary to slew each element to an extreme of its motion range to obtain a calibration zero reference. This is an undesirable situation. The initialization activity is time consuming. It requires the platform to assume a highly contorted configuration, and it does so by traveling through an unplanned and uncontrolled trajectory from an arbitrary initial configuration. The common solution to this problem is to provide absolute position sensors so that index marks on the incremental encoders can be found with a minimum of motion.

This project is divided into two parts: the selection and implementation of the hardware and the writing and integration of the software calibration routines with the CIRSSE Motion Control System (MCS). The selection of the hardware is complete. The linear position of the carriage will be measured using magnets attached to each carriage. The sensor is the Temposonics™ II Linear Displacement Transducer. It is manufactured by the Sensors Division of MTS Systems Corporation, Raleigh, NC. For the pan and tilt rotational motion, an optical encoder will be used. The sensor is the Model R96 Series, Absolute Encoder which resolves 1024 steps. It is manufactured by Robbins & Myers / Renco Company, Goleta, CA.

As far as implementation goes, the mechanical limit switch function will be augmented with a lightbeam sensor. When a mechanical switch is closed, the power to the platform is removed to stop the motion. During calibration it would be necessary to bypass this safety feature to be able to move the platform away from these stops. Although this is feasible, this safety bypass might be activated at the wrong time with disastrous results. Hence the calibration procedures will use lightbeam sensors to establish the calibration zero reference for each element. In this way the safety features of the mechanical limit switches need never by bypassed.

The calibration software routines are being written in two stages. The controller routines written by J. Consentino are being used to obtain a repeatable zero reference. Once the hardware is installed, the calibration procedures will utilize the lightbeam switches and the repeatable zero reference motions to obtain the absolute zero references. Thereafter, only incremental index mark procedures need to be used to locate the elements relative to the calibrated zero references.

Motion Control System Design

J. Watson, K. Fieldhouse and A. Desrochers

The objective of this project is to develop a software system for controlling the eighteen degrees of freedom associated with the dual arm robotic transporter system.

This year, the KALI robot control software (from McGill University) was installed, tested, and demonstrated on an eight degree of freedom system consisting of a six degree of freedom PUMA mounted on one of the two degree of freedom transporter carts. Based on this implementation, it was decided that using KALI for the eighteen degree of freedom system would require too many processors and extensive modifications.

Recently, a motion control system design team was formed. This group will retain some of the features of KALI and write new software to facilitate control of the dual arm testbed.

III. FACULTY, STAFF, STUDENTS

A. Faculty

GEORGE N. SARIDIS, Professor of ECSE and Director of CIRSSE; intelligent control systems, pattern recognition, computer systems, robotics, prostheses.

STEPHEN J. DERBY, Associate Professor of ME,AE,&M; mechanisms, kinematics and robotics, computer graphics, design.

ALAN A. DESROCHERS, Professor of ECSE and Associate Director of CIRSSE; performance analysis, robotics, control of automated manufacturing systems.

LESTER A. GERHARDT, Associate Dean of Engineering, Professor of ECSE and Computer Science; communication systems, sensor technology and integration, interactive, computer graphics, digital voice and image processing, adaptive systems, pattern recognition and computer integrated manufacturing.

HOWARD KAUFMAN, Professor of ECSE; digital control systems, adaptive systems applications and theory, optimal control.

ROBERT B. KELLEY, Professor of ECSE; robotic systems, machine intelligence, machine vision, expert systems.

L. KEN LAUDERBAUGH, Assistant Professor of ME,AE,&M; automatic control, manufacturing.

ARTHUR C. SANDERSON, Professor and Chairman of ECSE; robotics, knowledge-based systems, computer vision.

C.N. SHEN, Active Professor Emeritus of ECSE; navigation of mobile robots, laser ranging systems.

JOHN WEN, Assistant Professor of ECSE; multiple-arm manipulation and control, distributed parameter systems.

B. Students

1. Graduate Students

A. Behar
A. Bjanes
R. Buche
T. Cao
L. Carmichael
X. Chen
W. Cheng
C. Chung
J. Cosentino
K. Damour
A. Divelbiss
J. Farah
G. Hamlin
D. Hughes
H. Jungnitz
J. Kim
S. Krishnan
C. Kuo
K. Kyriakopoulos
D. LeFebvre

A. Lin
R. Mathur
J. McInroy
S. Miller
M. Mittman
M. Moed
R. Munger
S. Murphy
J. Newcomer
K. Nicewarner
J.R. Noseworthy
L. Page
J. Peck
J. Peiffer
B. Ravichandran
V. Ree
M. Repko
A. Ryan
M. Ryan
F. Schima

P. Sicard
D. Sood
R. Steinvorth
G. Sullivan
J. Tsai
T. Tsolkas
F. Wang
J. Watson
J. Weaver
L. Wilfinger

B. **Students** (continued)

2. Undergraduate Students

J. Bethel	N. Kothari
A. Dharmawan	R. Masiak
T. George	V. Rocha
D. Hammer	P.A.L. Silverthorne
M. Harvey	J. Zagorski
C. Koenig	

3. Students Graduated

<u>PhD</u>	<u>MS</u>	<u>U/G Retained in Program</u>
F. Wang	S. Miller	L. Carmichael
S. Murphy	R. Mathur	G. Hamlin
M. Moed	T. Tsolkas	A. Lin
	J. Cosentino	J. Newcomer
		J. Peck
		K. Damour
		J. Tsai

4. Visiting Scholars

Leonardo Lanari, Italy
Pedro Lima, Portugal
Josep Tornero, Spain
Sun Zengqi, China

C. Administrative and Technical Staff

Denise Elwell - Senior Secretary
Keith Fieldhouse - Software Engineer
Betty Lawson - Administrative Secretary
Steve Murphy - Post-Doctoral Research Associate
Ken Walter - Research Engineer

IV. TECHNOLOGY TRANSFER

A. Visits - January 1990 to Present

1. On Campus Visits

G.N. Saridis

Prof. Dr. Ing. Umberto Cugini, Consiglio Nazionale delle Ricerche, Italy - March 5, 1990
RIT Group - April 20, 1990
Dr. Hiroyuki Kano, Fujitsu Limited, Japan - May 3, 1990
Prof. Kocaoglan, I. Eksin, NATO Scholars from Turkey - May 3, 1990
Dr. Kosuge, Mitsubishi, Japan - June 26, 1990
Dr. J. Van Amerongen, Dr. Arunabha Bagchi, and Prof. Ir. C.J. Heuvelman, Twente University, Netherlands - June 29, 1990
Dr. R. Bravman, Symbol Technology - September 12, 1990
Prof. T. Vamos, National Academy of Hungary - November 27-30, 1990
Drs. K. Dawson, C. Schutz, and C. Karl, Jet Propulsion Laboratory - October 23, 1990

A.C. Sanderson

George Giralt, Laboratoire D'Automatique et D'Analyse Des Systemes, Toulouse Cedex, France - May 29, 1990

J. Wen

Jet Propulsion Laboratory - April 1990
Mr. Thuy Nguyen, Lockheed Company - August 1990
Professor Rod Grupen, University of Massachusetts at Amherst - November 1990
Mr. Richard Theobald, Lockheed Company - November 1990

L.A. Gerhardt

Jet Propulsion Laboratory - April 1990
NASA Langley - November 1990
NASA Langley, Johnson, Ames - November 1990
Mr. Dan Sydow - November 1990

H. Kaufman

Dr. J. Van Amerongen, Dr. Arunabha Bagchi, and Prof. Ir. C.J. Heuvelman, Twente University, Netherlands - June 29, 1990

2. Off Campus Visits

G.N. Saridis

NASA Headquarters, Annual Review - January 4-5, 1990
NASA Conference on Space '90, Directors Meeting - April 22-24, 1990
JPL/RPI Visit May 8-9, 1990
NASA Ames; Telerobotic Group Meeting - July 9-11, 1990

A.C. Sanderson

NASA Langley Visit - February 1990
JPL/RPI Visit - May 8-9, 1990

A. Desrochers

Lockheed Company - January 1990
Johnson Space Center - January 1990
McDonnell Douglas Space Systems - January 1990

J. Wen

Lockheed Company - January 1990
NASA Johnson Space Center - January 1990
McDonnell Douglas Space Systems Company - January 1990
NASA Langley Research Center - March 1990
Jet Propulsion Laboratory - May 1990

H. Kaufman

NASA Dryden - January 11, 1990
McDonnell Douglas Space Systems Company - January 12, 1990
NASA Langley - March 1-2, 1990
Eastman Kodak - May 15, 1990
University of Michigan - November 27, 1990

3. Major Conferences Attended

IEEE Conference on Information Sciences & Systems, Princeton University, March 21-23, 1990.

H. Kaufman

IEEE Conference on Robotics and Automation, Cincinnati, OH, May 13-18, 1990.

A.A. Desrochers	G.N. Saridis	A.C. Sanderson
S. Murphy	J. Wen	

Automatic Control Conference, San Diego, CA, May 23-25, 1990.

S. Murphy	J. Wen

IROS '90, Tsukaba, Japan, July 3-5, 1990.

A. Sanderson

IFAC Congress, Tallinn USSR, August 13-17, 1990.

A. Desrochers	G.N. Saridis

IEEE Intelligent Control Conference, Philadelphia, PA, September 7-8, 1990.

H. Kaufman	A. Sanderson	G.N. Saridis

SPIE Conference, Boston, MA, November 6-7, 1990.

A. Desrochers	S. Murphy	R. Noseworthy
L. Gerhardt	J. Wen	L. Page
R.B. Kelley	K. Kryiakopoulos	R. Steinvorth,

IEEE Conference on Decision and Control, Honolulu, Hawaii, December 5-8, 1990.

A. Sanderson	A. Desrochers	G.N. Saridis
H. Kaufman	S. Murphy	K. Kryiakopoulos

B. Publications - January 1990 to Present

1. Books

G.N. Saridis, Editor, *Advances on Automation and Robotics*, Vol.2, JAI Press, Greenwich, CT, December 1990.

G.N. Saridis, H. Stephanou (eds.), *Knowledge Based Robotic Control*, NATO ASI Series F, Springer-Verlag, December 1990.

2. Book Chapters

G.N. Saridis, "An Analytic Formulation of Knowledge Based Systems for Intelligent Machines", G.N. Saridis, H. Stephanou eds., *NATO ASI Series*, Springer Verlag, December 1990.

G.N. Saridis, "On the Revised Theory of Intelligent Machines", in *CTAT Festshrift*, F. Kozin, T. Ono eds., Winter 1990.

R.Y. Al-Jaar and A.A. Desrochers, "Petri Nets in Automation and Manufacturing", chapter in *Advances in Automation and Robotics*, Vol. 2, JAI Press, December 1990.

K. Valavanis and G.N. Saridis, "Knowledge-based Systems for Intelligent Control", *Advances in Automation and Robotics*, Vol. 2, JAI Press, December 1990.

A.C. Sanderson and L.S. Homem de Mello, "Automatic Generation of Mechanical Assembly Sequences", in *Geometric Modeling for Product Engineering*, editors: M. Wozny, J. Turner, and K. Price, pp. 461-482, New York, Elsevier, 1990.

A.C. Sanderson, "Real-Time Planning and Intelligent Control", G.N. Saridis, H. Stephanou eds., *NATO ASI Series*, Springer Verlag, December 1990.

R.B. Kelley, "2D Vision Techniques for the Handling of Limp Materials", a chapter in *Sensory Robotics for the Handling of Limp Materials*, P.M. Taylor Ed., NATO ASI Series, Vol. F64, Springer-Verlag, pp. 141-158, 1990.

R.B. Kelley, "Knowledge-Based Robot Workstation", Vol. 2, *JAI Press*, December 1990.

R.B. Kelley, "Knowledge-Based Robot Workstation", G.C.S. Lee ed., *NATO ASI Series*, Springer Verlag, December 1990.

3. Journal Articles

R.Y. Al-Jaar and A.A. Desrochers, "Performance Evaluation of Automated Manufacturing Systems Using Generalized Stochastic Petri Nets", *IEEE Transactions on Robotics and Automation*, Vol. 6, No. 6, pp. 621-529, December 1990.

J.E. McInroy and G.N. Saridis, "Acceleration and Torque Feedback for Robotic Control", *Journal of Robotic Systems*, J.Wiley & Sons, Vol. 7, No. 6, December 1990, pp. 813-832.

K.P. Valavanis and G.N. Saridis, "Probabilistic Modeling of Intelligent Robotic Systems", *IEEE Transactions on Robotics and Automation*, Vol. 6, No. 6, December 1990.

M. Moed, C. Stewart, and R.B. Kelley, "Reducing the Search Time of a Genetic Algorithm Using the Immigration Operator", *IEEE Transactions on Systems, Man, and Cybernetics*, December 1990.

J. Tornero, G. Hamlin, and R.B. Kelley, "Spherical-Object Geometry and Distance Computation for Robotic Applications", *IEEE Transactions on Robotics and Automation*, October 1990.

M.C. Moed and G.N. Saridis, "A Boltzman Machine for the Organizaton Level of Intelligent Machines", *IEEE Transactions of Systems, Man, and Cybernetics*, Vol. 20, No. 5, September/October 1990, pp. 1094-1102.

F. Wang and G.N. Saridis, "A Coordination Theory for Intelligent MAchines", *Automatica, The IFAC Journal*, Vol. 35, No. 5, September 1990, pp. 833-844.

J.E. McInroy and G.N. Saridis, "Reliability Analysis in Intelligent Machines", *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 20, No. 4, July 1990, pp. 950-956.

S. Derby, "Mechatronics for Robotics", *ASME Mechanical Engineering Magazine*, Vol. 112, No. 7, 40-43, July, 1990.

Y. Chen and A.A. Desrochers, "A Proof of the Structure of the Minimum Time Control Law for Robotic Manipulators Using a Hamiltonian Formulation", *IEEE Transactions on Robotics and Automation*, June 1990, Vol. 6, No. 3, pp. 388-393.

L.S. Homem de Mello and A.C. Sanderson, "AND/OR Graph Representation of Assembly Plans", *IEEE Transactions on Robotics and Automation*, Vol. 6, No. 2, April 1990, pp. 188-199.

A.C. Sanderson, L.S. Homem de Mello and H. Zhang, "Assembly Sequence Planning", *AI Magazine*, Special Issue on Assembly Planning, Spring, 1990, pp. 62-81.

S. Nayer, L. Weiss, D. Simon, and A.C. Sanderson, "Specular Surface Inspection Using STructured Highlight and Gaussian Images", *IEEE Transactions on Robotics and Automation*, Vol. 6, No. 2, April 1990, pp. 208-218.

D. Sood, M. Repko and R.B. Kelley, "Integrated Sensing for Circuit Board Insertion", *Journal of Robotic Systems*, 7(3), June 1990, pp. 487-505.

P. Dupont and S. Derby, "Two-Phase Path Planning for Robots with Six or More Joints", *ASME Journal of Mechanical Design*, Vol. 112, No. 1, 50-58, March 1990.

4. Conference Proceedings

A. Desrochers, "Analysis of the Joint Probability Density Function of the Inventory in a Two Machine Two Buffer Transfer Line with Unreliable Machines", *Proceedings of the 29th IEEE Conference on Decision and Control*, December 5-7, 1990, Honolulu, Hawaii.

S.H. Murphy, J.T. Wen, G.N. Saridis, "Simulation and Analysis of Flexibly Jointed Manipulators", *Proceedings of the 29th Conference on Decision and Control*, Honolulu, Hawaii, December 1990.

S. Murphy, J. Wen, and G.N. Saridis, "Analysis and Control of Flexibly Jointed Manipulators," *Conference on Decision and Control*, Honolulu, Hawaii, December 1990.

J. Wen, "A Unified Perspective on Robot Control: The Energy Lyapunov Function Approach", *Conference on Decision and Control*, December 1990.

K. Kyriakopoulos, G.N. Saridis, "Minimun Jerk Trajectory Planning for Robotic Manipulators", *1990 SPIE Conference on Robotics*, Boston, MA, November 1990.

A. Desrochers, "Experimental Testbed for Cooperative Robotic Manipulators", *Proceedings of the SPIE Symposium on Cooperative Robotics in Space*, November 4-9, 1990, Boston, Massachusetts.

A. Desrochers, "Performance Evaluation of Robotic and Manufacturing Systems", *Proceedings of the 1990 Sympsoium on Control of Robots and Manufacturing Systems*, (invited), University of Texas at Arlington, The Automation and Robotics Research Institute, November 9, 1990, Fort Worth, Texas.

R. Mathur and A.C. Sanderson, "A Hierarchical Planner for Space Truss Assembly", *Proceedings of the 1990 SPIE Symposium on Advances in Intelligent Systems*, Boston, MA, November 1990.

K. Shrinivas and S. Derby, "Robotic Assembly of Gears", *SME Automated Assembly Conference Proceedings*, Vol. 1, November 1990.

R. Mathur, and A.C. Sanderson, "A Hierarchical Planner for Space Truss Assembly", *Proceedings 1990 SPIE Symposium on Advances in Intelligent Systems*, Boston, MA, November 5-6, 1990.

J.R. Noseworthy, and L.A. Gerhardt, "Three-Dimensional Vision Requirements and Applications In A Space Environment", *SPIE Conference*, Boston, MA, November 1990.

L. Page, and C.N. Shen, "Analysis of Terrain Map Matching Using Multisensing Techniques for Applications to Autonomous Vehicle Navigation". *Proceedings OE/Boston Symposium on Advances in Intelligent Systems, Conference on Sensors Fusion III: 3-D Perception and Recognition*, SPIE, Boston, MA, November 1990.

S. Derby, "New Teaching Methods for Assembly Robots", *SME Robots 14 Conference Proceedings*, Vol. 1, November 1990.

K. Shrinivas and S. Derby, "Robotic Assembly of Gears", *SME Automated Assembly Conference Proceedings*, Vol. 1, November 1990.

J. Tsai, J. Bethel, J. Peiffer, and R.B. Kelley, "Gripper for Truss Structure Assembly," *Proceedings of SPIE Conference: Cooperative Intelligent Robotics in Space*, Vol. 1387, Cambridge, MA, November 1990 (in press).

R. Steinvorth, G. Neat, and H. Kaufman, "Model Reference Adaptive Control of Flexible Robots in the Presence of System Load Changes", *SPIE Symposium on Advances in Intelligent Systems*, Boston, November 1990.

F.Y. Wang, G.N. Saridis, "Task Plan Generation for Intelligent Machines", *Proceedings of the 5th Symposium on Intelligent Control*, Philadelphia, PA, September 1990.

J.E. McInroy, G.N. Saridis, "Reliable High Precision Positioning of Intelligent Machines", *Proceedings of the 5th Symposium on Intelligent Control*, Philadelphia, PA, September 1990.

K. Kyriakopoulos, G.N. Saridis, "On-line Motion Planning for Mobile Robots in Non-Stationary Environments", *Proceedings of the 5th Symposium on Intelligent Control*, Philadelphia, PA, September 1990.

S. Miller, G.N. Saridis, "PRIME: A Bottom-up Approach to Probabilistic Rule Development", *Proceedings of the 5th Symposium on Intelligent Control*, Philadelphia, PA, September 1990.

J. Ducoste and S. Derby, "A Docking End Effector for a Two Arm Robot", *ASME Mechanism Conference Proceedings*, DE-Vol. 26, 271-278, September 1990.

K.P. Valavanis, G.N. Saridis, "A Review of Intelligent Control-based Methodologies for Modeling and Analysis of Hierarchically Intelligent Systems", *Proceedings of the 5th Symposium on Intelligent Control*, Philadelphia, PA, September 1990.

E. Barney and H. Kaufman, "Model Reference Adaptive Control of Cardiac Output and Blood Pressure Thru Two Drug Infusions", *5th International Symposium on Intelligent Control*, Philadelphia, September 5-8, 1990.

J. Ducoste, and S. Derby, "A Docking End Effector for a Two Arm Robot", *ASME Mechanism Conference Proceedings*, DE-Vol. 26, 271-278, September 1990.

H. Kaufman and E. Barney, "Model Reference Adaptive Control of Cardiac Output and Blood Pressure Thru Two Drug Infusions", *5th IEEE International Symposium on Intelligent Control*, Philadelphia, 5-8 September 1990.

L.K. Lauderbaugh, and J. Sullivan, "I_BPEX: Interactive Process Expert", *Proceedings at IEEE Symposium on Intelligent Control 1990*, Philadelphia, PA, September 5-8, 1990.

F. Wang, G.N. Saridis, "A Coordination Theory for Intelligent Machines", *Proceedings of the 1990 IFAC Congress*, Tallinn, USSR, August 1990.

K. Kyriakopoulos, G.N. Saridis, "Minimum Distance Estimation and Collision Prediction", *Proceedings of the 1990 IFAC Congress*, Tallin, USSR, August 1990.

G.N. Saridis, "Theory of Intelligent Machines", *Proceedings of the 1990 International Workshop on Intelligent Motion Control*, Instanbul, Turkey, August 1990.

R.Y. Al-Jaar and A.A. Desrochers, "A Methodology for Evaluating Decision Making Architectures for Automated Manufacturing Systems", *Proceedings of the 11th IFAC World Congress*, Tallinn, Estonia, USSR, August 13-17, 1990, Vol. 10, pp. 39-44.

P. Shah, R. Kraft, and S. Derby, "Development of Part Acquisition and Insertion Routines Using the AIM Database", *ASME Computers in Engineering Conference Proceedings*, Vol. 1, 399-404, August, 1990.

S. Derby, "Selective Use of Mechatronics When Designing Assembly Robots", *ASME Computers in Engineering Conference Proceedings*, Vol. 1, 579-582, August, 1990.

P. Shah, R. Kraft, and S. Derby, "Development of Part Acquisition and Insertion Routines Using the AIM Database", *ASME Computers in Engineering Conference Proceedings*, Vol. 1, 399-404, August 1990.

S. Derby, "Selective Use of Mechatronics when Designing Assembly Robots", *ASME Computers in Engineering Conference Proceedings*, Vol. 1, 579-582, August 1990.

J. Wen and S. Murphy, "Robot Force Control in the Presence of Environmental Flexibility," *6th Yale Workshop on Applications of Adaptive Systems Theory*, August 1990 (Invited Paper).

E. Castro, A. Desrochers, S. Seereeram, J. Singh, and J. Wen, "A Real Time Control Architecture for a Robotic Filament Winding System", *Proceedings of the Third International Symposium on Robotics and Manufacturing*, (invited), July 18-20, 1990, Vancouver, British Columbia, Canada.

Y. Chen and A. Desrochers, "Structure of Time Optimal Control of Two Coordinated Arms Handling a Common Object Along a Specified Path", *Proceedings of the Third International Symposium on Robotics and Manufacturing*, July 18-20, 1990, Vancouver, British Columbia, Canada.

Willis, J.C., A.C. Sanderson, and C. Hill, "Cache Coherence in Systems with Parallel Communications Channels and Many Processors", *Proceedings of IEEE Supercomputing '90 Conference.*

L.S. Homem de Mello and A.C. Sanderson, "Evaluation and Selection of Assembly Plans", *Proceedings of 1990 IEEE International Conference on Robotics and Automation*, Cincinnati, OH, May 1990.

J. Robinson and A. Desrochers, "Performance Analysis of a Robotic Testbed Control Architecture", *Proceedings of the 1990 IEEE International Conference on Robotics and Automation*, May 13-18, 1990, Cincinnati, Ohio, pp. 1782-1787.

S. Murphy, J.T. Wen, G.N. Saridis, "Simulation of Cooperative Robot Manipulators on a Mobile Platform", *Proceedings of the 1990 Conference on Robotics and Automation*, Cincinnati, OH, May 1990. One of six finalists, best paper award.

D. Simon, L. Weiss and A.C. Sanderson, "Self-Tuning of Robot Program Parameters", *Proceedings of 1990 IEEE International Conference on Robotics and Automation*, Cincinnati, OH, May 1990.

J. McInroy, G.N. Saridis, "Reliability Analysis in Intelligent Machines", *Proceedings of the 1990 Conference on Robotics and Automation*, Cincinnati, OH, May 1990.

J. McInroy, T. Bryan, G.N. Saridis, "Momentums Limiting Velocity Controls for Robotic Manipulators", *Proceedings of the 1990 Conference on Robotics and Automation*, Cincinnati, OH, May 1990.

S.H. Murphy, J.T. Wen, G.N. Saridis, "Recursive Calculations of Geared Robot Manipulator Dynamics", *Proceedings of the 1990 Conference on Robotics and Automation*, Cincinnati, OH, May 1990.

J. Wen and S. Murphy, "Position and Force Control of Robot Arms," *American Control Conference*, May 1990.

J. Wen and X. Chen, "The Optimal Multiplier Method for Nonlinear Robustness Analysis," *American Control Conference*, May 1990.

J. Wen and S. Murphy, "Position and Force Control of Robot Arms," *IEEE Robotics and Automation Conference*, May 1990.

S. Murphy, J. Wen, and G.N. Saridis, "Recursive Calculation of Forward Dynamics for Geared Robot Manipulators," *IEEE Robotics and Automation Conference*, May 1990.

S. Murphy, J. Wen, and G.N. Saridis, "Simulation of Cooperating Robot Manipulators on a Mobile Platform," *IEEE Robotics and Automation Conference*, May 1990.

K. Kyriakopoulos and H. Kaufman, "A Practical Approach for Minimum Time Control of the Spacecraft Labortory", *1990 Conference on Information Sciences and Systems*, Princeton University, March 21-23, 1990.

H. Kaufman, "Comparative Analysis of Two Factorization Procedures for Identification of Non-Casual Image Blurs", (with Wagner, Wellstead, Tekalp), 1990 *Conference on Information Sciences and System*, Princeton University, March 21-23, 1990.

H. Kaufman, "Multiple-Model Adaptive Control Applied to the Multiple-Drug Infusion Problem:, (with Yu, Roy, Bequette), *1990 Conference on Information Sciences and Systems*, Princeton University, March 21-23, 1990.

L. Gerhardt, "The Use of Pre-Conditioned Structured Light for Three-Dimensional Vision", *Manufacturing International Conference*, Atlanta, GA, March 1990.

L. Page and C.N. Shen, "Fusion of Gross Satellite Sensing and Laser Measurements by Skyline Map Matching for Autonomous Unmanned Vehicle Navigation". *Proceedings of SPIE's 1990 Symposium Remote Sensing and Signal and Image Processing*, Orlando, Florida, April 1990.

H. Kaufman, "Time Optimal Contour Tracking for Machine Tool Controllers", (with Imamura), *Proc. 1990 ACC*, San Diego, May 1990, pp. 1103-1108.

R. Steinvorth, G. Neat, and H. Kaufman, "Direct Model Reference Adaptive Control with Application to Flexible Robots", *IASTED Conference on Adaptive Control and Signal Proceedings*, NY, October 1990.

5. CIRSSE Reports

"Recursive Calculation of Geared Robot Manipulator Dynamics", by S.H. Murphy and J.T. Wen; January 1990.

"A Petri-Net Coordination Model of Intelligent Mobile Robots", by F.Y. Wang, K.J. Kyriakopoulos, A. Tsolkas and G.N. Saridis; January 1990.

"The Attitude Control Problem", by J.T. Wen and K. Kreutz-Delgado; January 1990.

"Simulation of Cooperating Robot Manipulators on a Mobile Platform", by S.H. Murphy, J.T. Wen, and G.N. Saridis; February 1990.

"Stability Analysis of Position and Force Control for Robot Arms", by Steve H. Murphy and John T. Wen; May 1990.

"PID Control for Robot Manipulators", John T. Wen and Steve Murphy; May 1990.

"PRIME: A Bottom-Up Approach to Probabilistic Rule Development", by Scott A. Miller; May 1990.

"Simulation and Analysis of Flexibly Jointed Manipulators", by John T. Wen and Steve T. Murphy; May 1990.

"A Hierarchical Planner for Space Truss Assemblies", by Rajive K. Mathur; May 1990.

"On the Revised Theory of Intelligent Machines", by George N. Saridis; June 1990.

"A Coordination Theory for Intelligent Machines", by Fei-Yue Wang; August 1990.

"Generation of Rotational Sweep Shadows for Polyhedrons", by Henry L. Welch and Robert B. Kelley; August 1990.

"The Analysis of Potential Mating Trajectories and Grasp Sites", by Henry L. Welch and Robert B. Kelley; August 1990.

"Development of a Control System for a Pair of Robotic Platforms", James L. Cosentino; August 1990.

"Collision Avoidance of Mobile Robots in Non-Stationary Environments", K.J. Kyriakopoulos and G. N. Saridis; September 1990.

"Spherical-Object Representation and Fast Distance Computation for Robotic Applications", Josep Tornero; September 1990.

"A Novel Representation for Planning 3-D Collision-Free Paths", Susan Bonner and Robert B. Kelley; September 1990.

"Asymptotically Stable Direct Model Reference Adaptive Controllers for Processes Not Necessarily Satisfying a Positive Real Constraint", Howard Kaufman, and Gregory W. Neat; October 1990.

"Asymptotically Stable Multiple Input-Multiple Output Direct Model Reference Adaptive Controller for Processes Not Necessarily Satisfying a Positive Real Constraint", Howard Kaufman, Gregory W. Neat, and Rodrigo Steinvorth; October 1990.

"Model Reference Adaptive Control of Flexible Robots in the Presence of Sudden Load Changes", Rodrigo Steinvorth, Howard Kaufman and Gregory W. Neat; October 1990.

"Reducing the Search Time of a Genetic Algorithm Using the Immigration Operator, Michael C. Moed, Charles V. Stewart, and Robert B. Kelley; October 1990.

"Gripper for Truss Structure Assembly", Robert B. Kelley, Jodi Tsai, Jeff Bethel, and John Peiffer; October 1990.

"Fusion of Gross Satellite Sensing and Laser Measurements by Skyline Map Matching for Autonomous Unmanned Vehicle Navigation", C.N. Shen and Lance Page; October 1990.

"Skyline-Based Terrain Matching Using a Max-Min Principle", C.N. Shen and Lance Page; October 1990.

"Analysis of Terrain Map Matching Using Multisensing Techniques for Applications to Autonomous Vehicle Navigation", Lance Page and C.N. Shen; October 1990.

"Three Dimensional Vision - Requirements and Applications in a Space Environment", J. Russell Noseworthy and Lester A. Gerhardt; November 1990.

"Nonlinear Dynamical Model and Control for a Flexible Beam", Feiyue Wang and John T. Wen; November 1990.

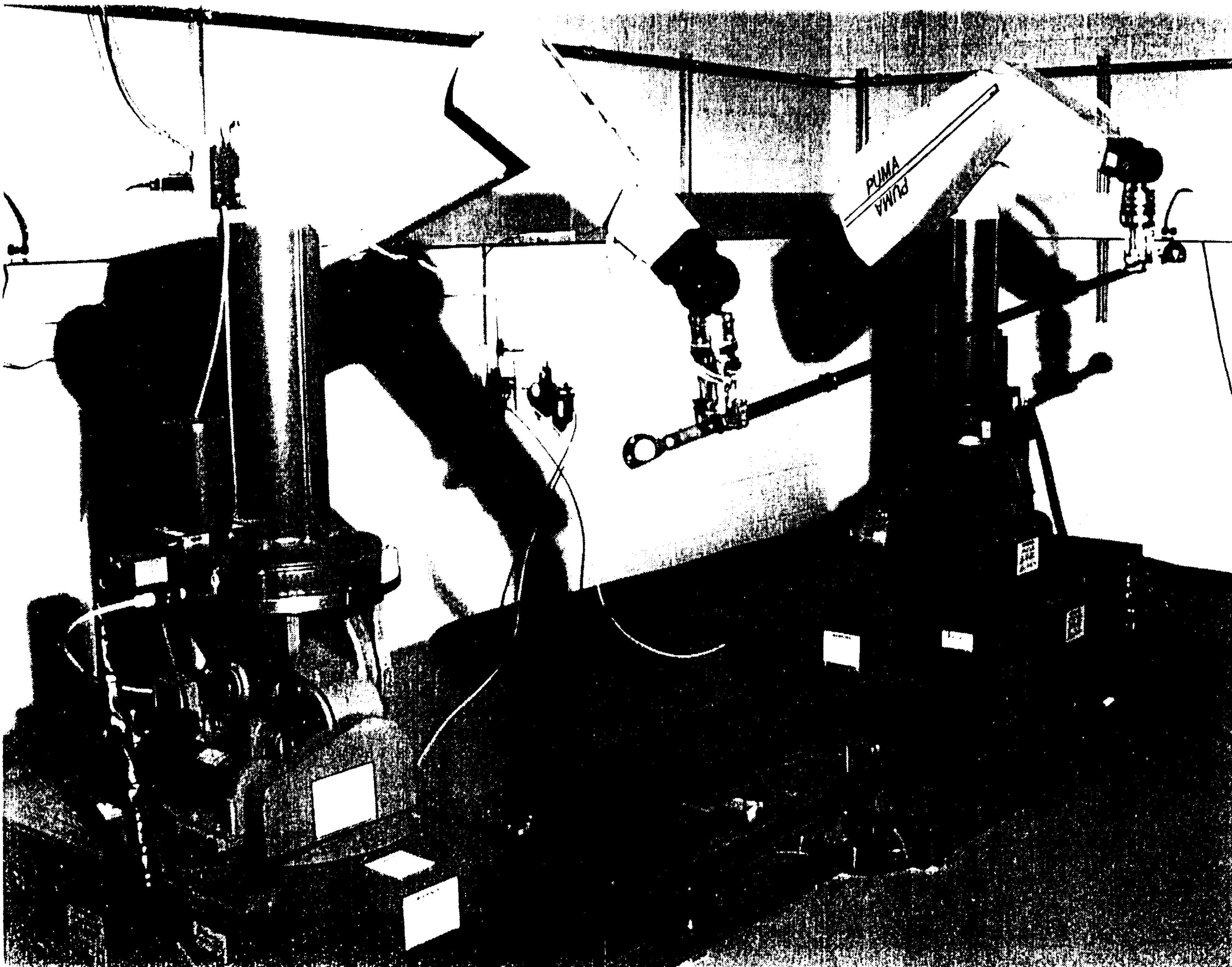
V. EXTERNAL FUNDING

A. Proposals Funded

NASA Goddard - L.K. Lauderbaugh - $18,000
NASA Marshall - G.N. Saridis; J. McInroy - $18,000
NASA Lewis - L.K. Lauderbaugh; J. Sullivan - $11,500
NASA Johnson - J. Wen - $24,000
NY Center for Advanced Technology in Automation and Robotics - S. Derby; A. Desrochers; R.B. Kelley; L.K. Lauderbaugh; A.C. Sanderson; J. Wen - $135,620
NSF - J. Wen - $70,000
Rome Air Development Center - A.C. Sanderson - $100,000
Defense Logistics Agency - A.C. Sanderson - $300,000

B. Gifts

McDonnell Douglas Foundation - October 1990 - $4,333.00


PUMA

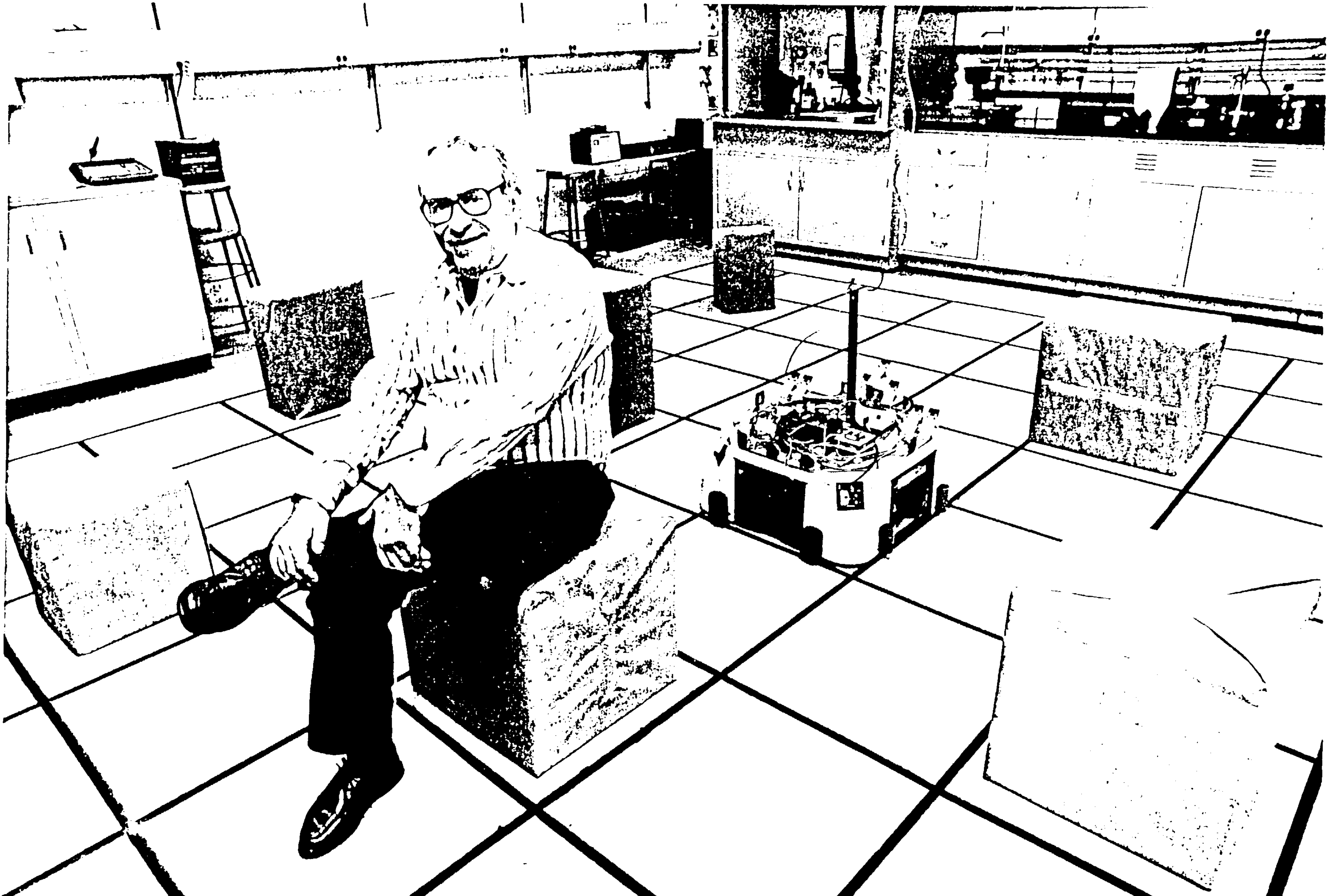


FIGURE 4

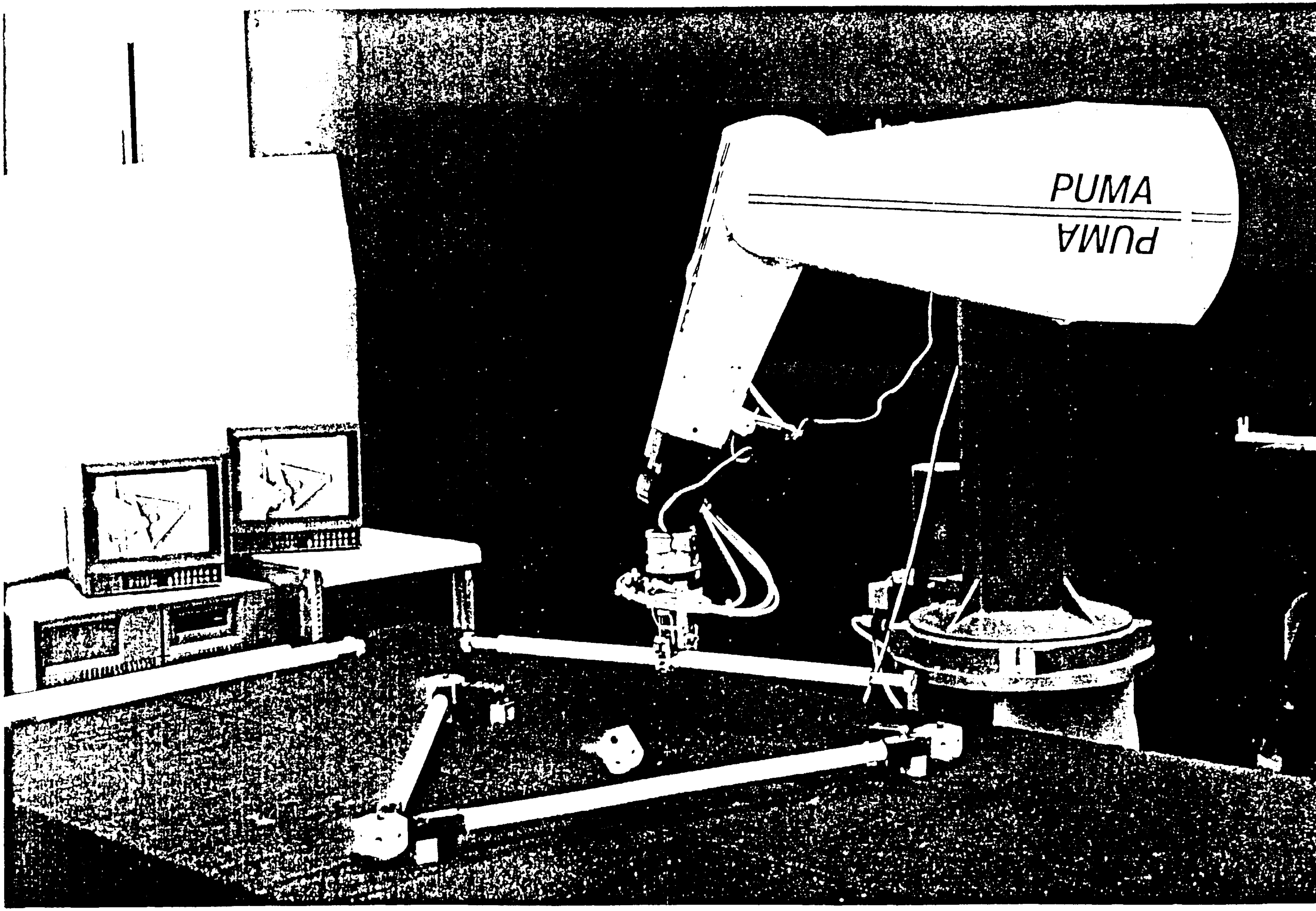


FIGURE 5

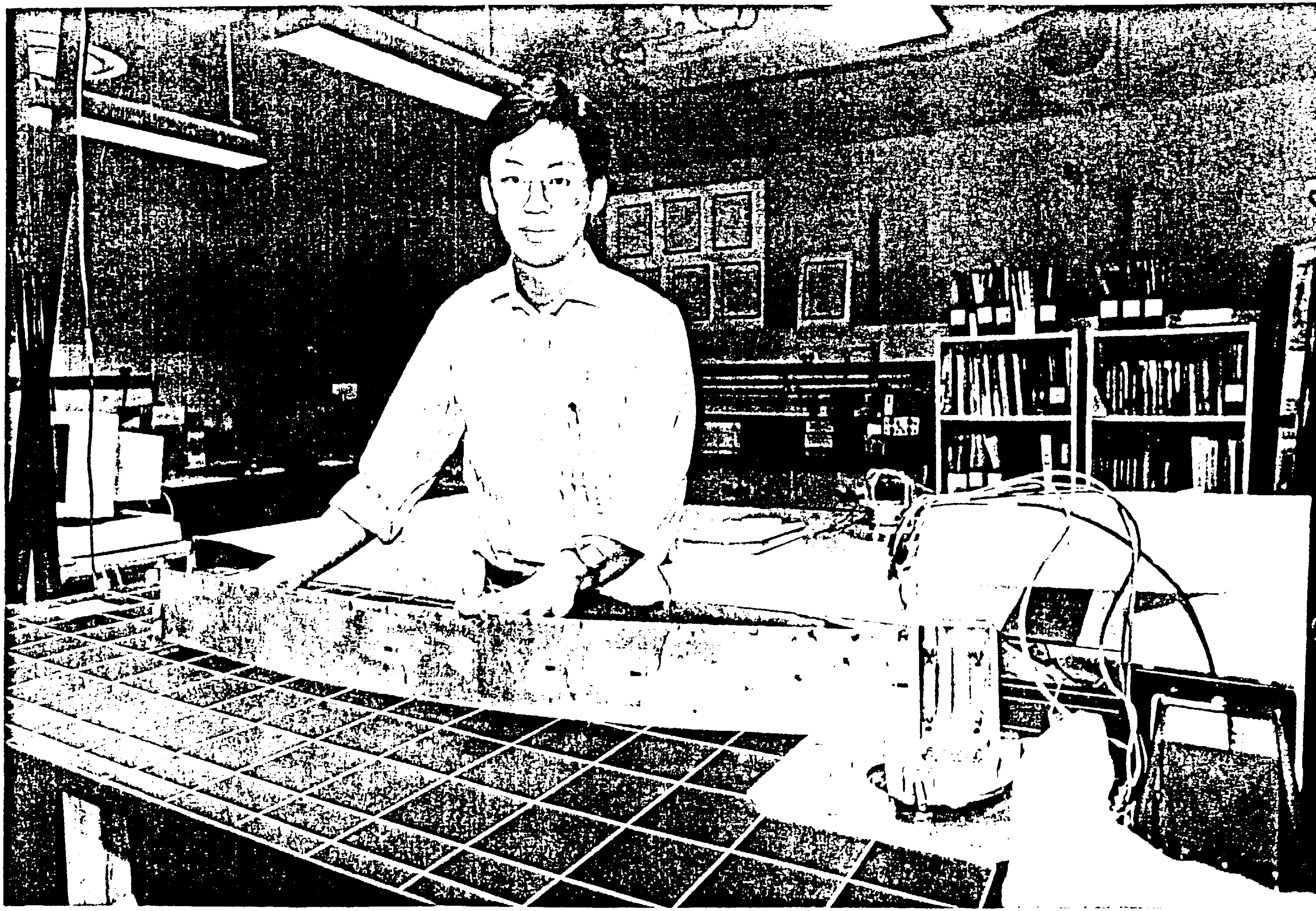


FIGURE 6

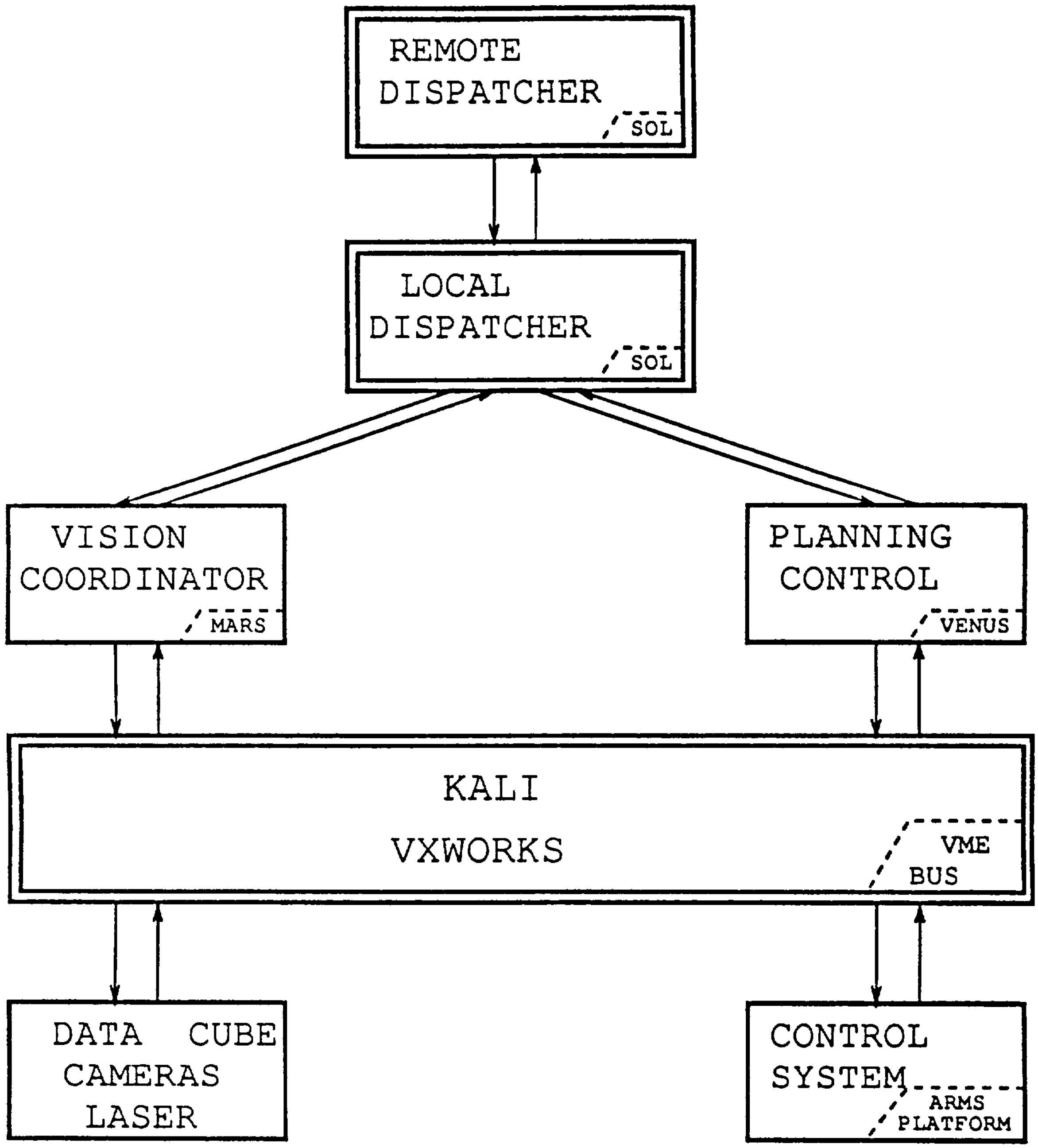
in space. This has been complemented by useful simulations of control situations in gravitationless and atmosphere empty environments.

Since the project is in full development the next year is expected to be spent in continuing the work presently in progress. However, in more detail, the following projects are planned to be pursued for the next year.

Theoretical work will be continued in developing the Petri-net coordinators and the software necessary for their communication, so that sensory-motion-planning coordination can be accomplished. A remote dispatcher will be tested for telerobotic control of the testbed. This project will serve as a step towards a possible joint project with JPL, to remotely control a teleoperation with minimal communication bandwidth. Figure 7 depicts this idea.

Further theoretical work is needed in order to develop an integrated and expanded system for multiarm motion control to replace KALI. A Design Team has been organized and are looking into the architecture and software development of such a system. Adaptive control for reduced order models and uncertain loading conditions will also be studied.

Task planning is another area of continuing interest both theoretically and as it applies to our three case studies. Such effort will continue with emphasis on real time dynamic object avoidance, assembly and replanning for unpredictable situations. Simulations will provide a strong tool to anticipate space situations.



T E L E R O B O T I C S
T E S T B E D   C O N F I G U R A T I O N

Figure 7

In terms of applications of theoretical results the dual arm testbed will be equipped with its Petri-net coordinators and tests should be made in integrating the activities of the vision, motion control, and planning systems. Calibration of the systems is a major task, and closed-loop servoing using the vision system will be tested.

The mobile robot platform will have a camera installed and its hardware worked out for future work on visual collision avoidance, navigation, and safety studies. Some of the existing planning algorithms should be adapted for this project.

The vision project will continue by investigating real-time image processing through the Datacube and use for real-time visual servoing and 3-D assembly. Lighting effects particular to space assembly will be examined and tested with the system.

Finally, the CIRSSE grippers, designed and built to handle space assembly and endowed with force and proximity sensors will have their controls fully developed and integrated into the assembly process.

In summary, next year will be devoted to developing the first step in motion-vision-sensor-planning integration, and at the same time completing the details of the individual components of the systems. This will be the first test of the implementation of the Intelligent Machine for Space Exploration, the final goal of our research.

VII. APPENDICES

APPENDIX A: Advisory Board/Recommendation

January 2, 1991

To: Dr. G. A. Saridis, Director of CIRSSE

From: CIRSSE ADVISORY COMMITTEE

Subject: Report on Progress during 1990

The Advisory Committee submits the following comments on the work of CIRSSE during 1990, based on the Annual Conference held on November 29-30 and review of videotapes and publications:

1. Overall technical quality

The Committee is impressed with the high quality of the research being conducted by CIRSSE faculty and graduate students. You have clearly assembled a very strong research team. The quality of the work is evidenced also by the number of technical papers and high-quality conference publications resulting from the work.

At the core of the research is the theory of intelligent control and its implementation in hierarchical structures, which embody the principle of "decreasing intelligence with increasing precision". We believe that the principles of hierarchical control, which are also consistent with the NASREM architecture, are clearly appropriate for NASA systems. Furthermore, while the NASREM architecture is only conceptual, the CIRSSE hierarchical architecture has been actually implemented! The development of analytical principles and their application in robotic systems are significant contributions to the field.

2. Comments on specific projects

2.1 Dual arm control

The demonstration of the 18 degree of freedom dual arm system was quite impressive, as was the assembly of space-station struts and the ability of the redundant robot to maintain a nearly constant end effector position in the presence of base motion. Considerable progress was evident in the software structure (based on the KALI system) and its ability to integrate vision data with robot control parameters. The special purpose hand for strut grasping and assembly appears to be well done. On the other hand, most of the software developed to date seems to be concerned with kinematic problems, and considerable work still needs to be done to obtain real time dynamic control of the dual arm system.

It is apparent that the development and installation of the hardware and software for this large system has been a major undertaking, perhaps larger than initially anticipated. The integration of the two robots with the Aronson platform, 5 cameras, laser ranging, force-torque sensing and compliant control, trajectory planning and obstacle avoidance is a very large task. We believe that it will be desirable to have significant NASA input to this project in the event of major structural changes to the design of the space station, to insure that the research results remain applicable.

2.2 Flexible arm control

This is a strong research project, both in its theoretical and implementation aspects. The mathematical models developed by Prof. Wen appear to be excellent, since the simulations of the motion of the flexible beam agree very closely with experimental measurements. However, since current and planned NASA manipulators employ stiff links, the results may not be directly applicable. We suggest that the project be modified in order to also investigate manipulators where the flexibility is concentrated in the joints, and the links remain stiff. The possibility of cooperation with JPL on such a project, especially in connection with the Space Shuttle arm, should be investigated.

2.3 Vision and sensing

There are a number of strong vision and sensing projects, directed by Professors Sanderson, Gerhardt, Kaufman, Derby and others. The presentations of work on reducing the effects of camera jitter and calibration errors, image matching using minimal representations, and restoration of distorted depth and motion fields were excellent. The graduate students working on these projects seem to be outstanding. In order to make the work more relevant to NASA missions, we suggest investigations under illumination conditions which simulate lunar or planetary environments.

2.4 Mobile robot laboratory

This laboratory uses a TRC Labmate as a platform. On-board cameras and proximity sensors are used to locate and map the obstacles in the field, and a human operator then steers the vehicle to navigate safely around the obstacles. Fully automatic navigation and control are planned for the future. This project does not appear to the Committee to be in the forefront of work in the field. Excellent algorithms for navigation around obstacles exist and it is not clear where the contribution of this project lies. On the other hand, we understand that this is a relatively new project, and that it takes time to establish a new laboratory. In order to make the work relevant to NASA missions, it might be interesting to study the mapping and obstacle avoidance behavior of the system under simulated lunar illumination, and with terrain which simulates some of the problems which may be encountered, e.g., rocks or sandy soil where wheels may slip.

3. Industry contacts and technology transfer

Nearly all the work at CIRSSE is sponsored by NASA and other government agencies, and there appears to be relatively little industrial interaction. The "Day with CIRSSE" held in March 1989 attracted a number of industrial visitors, but there has not been much followup. We believe that this a serious problem, which arises from two major sources: (1) the major strength of the Center is in the high quality of its theoretical contributions, and (2) lack of emphasis on industrial contacts and technology transfer.

In view of the strong industrial contacts available through other Centers at RPI (including the Center for Advanced Technology, the Center for Computer Integrated Manufacturing and the Advanced Manufacturing Center), as well as access to NASA contractors, we believe it should be possible to develop a stronger industrial outreach. As a step in this direction, we recommend an annual "*Technology Transfer Day*", in which software and devices developed at CIRSSE are displayed and discussed, with an emphasis on methods of transferring them to industry. It appears to us that the work on some aspects of the vision and sensing program, hierarchical control algorithms, gripper design, dual arm coordination methods and other projects is approaching the point where there may be significant industrial interest. Clearly, software developed by graduate students may not be suitable for commercial distribution.

However, if there is industrial interest, it may be possible to develop joint projects involving CIRSSE, one of the more applied RPI Centers and industry, to transfer the innovations to the commercial sector.

4. NASA interaction

We believe it is important for NASA to maintain strong interaction with CIRSSE, not limited to attendance at annual research reviews. In view of the termination of the telerobotic testbed project at JPL and probable major changes in the FTS and space station programs, such interaction has become critical. It is understood that the primary goals of the Center have been education and research. However, now that the basic infractructure of the Center has been developed, the time has come for CIRSSE research projects to move closer to actual NASA problems. Such involvement wil be crucial to the future of CIRSSE once its basic Center Grant expires. Several ways in which such a shift in emphasis can be achieved are indicated in the review of specific projects in Section 2 above.

5. Summary

The Center has a significant record of research accomplishment in its relatively short life. The research projects are strong and promise to make important contributions to the theory and applications of intelligent control. The Center has now matured to the point where its research can be more closely related to NASA applications in space. We also recommend a stronger emphasis on technology transfer to industry.

Respectfully submitted,

A. K. Bejczy
G. A. Bekey
A. Meintel

APPENDIX B: Conference Agenda

NASA Center for Intelligent Robotic Systems for Space Exploration Conference Agenda

Rensselaer Polytechnic Institute

Center for Industrial Innovation, Suite 4050
Troy, New York 12180-3590

Thursday, November 29, 1990

1:00-1:15pm	Welcome *George N. Saridis*
1:15-2:00pm	Keynote Speaker - Epistemic Background of Problems of Uncertainty *Dr. Tibor Vamos*, Member of Hungarian Academy of Science
2:00-2:30pm	CIRSSE Research Overview *George N. Saridis*
2:30-3:00pm	CIRSSE Laboratory Overview *Alan A. Desrochers*
3:00-3:15pm	BREAK
3:15-5:00pm	SESSION 1: VISION *Chairman--Lester A. Gerhardt* 3D Sensing and Space Based Applications; *J. Russell Noseworthy and Lester A. Gerhardt* Minimal Representation Methods for Image Matching in 2D and 3D; *B. Ravichandran and Arthur Sanderson* Restoration of Distorted Depth Maps Calculated From Stereo Sequences; *Kevin Damour and Howard Kaufman*
5:00-6:00pm	Laboratory Demonstrations for Advisory Committee
7:00pm	Dinner - Faculty/Staff Dining Hall

Friday, November 30, 1990

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8:00am	CONTINENTAL BREAKFAST
8:30-9:15am	Keynote Speaker - Space Station Freedom Robots and Their Role in External Maintenance *Charles Price*, NASA Johnson Space Center
9:15-10:15am	SESSION 2: DUAL ARM CONTROL *Chairman--Steve Derby* Dual Arm Path Planning; *Francis Schima and Steve Derby* Dual Arm Modeling; *Steve Murphy and George N. Saridis*
10:15-10:30am	SESSION 3: TECHNOLOGY TRANSFER *Chairman--Alan A. Desrochers* Commercial Applications of Flight Telerobotic Servicer Technologies; *K.Z. (Brad) Bradford, Martin Marietta*
10:30-10:45am	BREAK (COFFEE/TEA/JUICE)
10:45-12:15	SESSION 4: TELEROBOTICS TESTBEDS *Chairman--John Wen* JPL Telerobot Testbed: Lessons Learned; *Bob Balaram, JPL* Goddard Robotics Laboratory; *Michael Ali, Goddard* Automated Structures Assembly Laboratory; *Ralph Will and Al Meintel, NASA Langley Research Center*
12:15-1:00pm	LUNCH
12:15-1:45pm	ADVISORY COMMITTEE LUNCH
1:00-1:45pm	Lab Demonstrations
1:45-2:45pm	SESSION 5: CONTROL AND INTEGRATION *Chairman--Alan A. Desrochers* Robotic Planning; *Mike Moed and Robert B. Kelley* CIRSSE Testbed: Motion Control Systems (MCS); *Jim Watson, Keith Fieldhouse, and Alan A. Desrochers*
2:45-3:00pm	BREAK
3:00-4:00pm	SESSION 6: ASSEMBLY *Chairman--Arthur Sanderson* Assembly Planning for Space Truss Structures; *Arthur Sanderson* Selection of a Truss Joint for Robotic Assembly of Space Structures; *George Parma, NASA Johnson Space Center*
4:00pm	Concluding Remarks *George N. Saridis*

Symposium on Advances in Intelligent Systems

Program on Telerobotics

Program Chair:

Charles Price, NASA/ Johnson Space Ctr.

Conference 1387 • Two Days • SPIE Proceedings Vol. 1387 • Tuesday-Wednesday 6-7 November 1990

Cooperative Intelligent Robotics in Space

Conference Chairs: Rui J. P. de Figueiredo, Rice Univ. William E. Stoney, MITRE Corp. *Program Committee:* Rodger A. Cliff, Lockheed Missiles & Space Co., Inc.; Phillip C. Daley, Martin Marietta Corp.; Michael Hollars, Ford Aerospace; Avinesh C. Kak, Purdue Univ.; George M. Levin, Office of Space Flight/NASA Headquarters; Dudley G. McConnell, Office of Space Science and Applications/NASA Headquarters; Jeffrey D. Rosendhal, Office of Exploration/NASA Headquarters; George N. Saridis, Rensselaer Polytechnic Institute; Thomas Sheridan, Massachusetts Institute of Technology; Robert Sirko, McDonnell Douglas Space Systems Co.; David G. Stuart, TRW, Inc.; Gregory E. Swietek, Office of Space Station/NASA Headquarters; Delbert Tesar, Univ. of Texas/ Austin; Ian D. Walker, Rice Univ.

TUESDAY 6 NOVEMBER 1990

SESSION 1 . . . . Tues. am

Experiments in Robotic Assembly of Truss Structures in Space

Organizer and Chair: Alan A. Desrochers, Rensselaer Polytechnic Institute

Experimental testbed for cooperative robotic manipulators, A. A. Desrochers, J. Cosentino, Rensselaer Polytechnic Institute . . . . [1387-01]

Analysis of cooperative robotic manipulators on a mobile platform, S. Murphy, J. Wen, G. N. Saridis, Rensselaer Polytechnic Institute . . . . [1387-02]

Three-dimensional vision requirements and applications in a space environment, L. Gerhardt, J. Wen, G. N. Saridis, Rensselaer Polytechnic Institute . . . . [1387-03]

Gripper for truss structure assembly, R. B. Kelley, Rensselaer Polytechnic Institute . . . . [1387-04]

Hierarchical planner for space truss assembly, R. Mathur, A. C. Sanderson, Rensselaer Polytechnic Institute . . . [1387-05]

WEDNESDAY 7 NOVEMBER 1990

Please note that Session 5 and Session 6 are concurrent.

SESSION 5 . . . . Wed. am

Intelligent Control

Organizer and Chair: Kimon P. Valavanis, Northeastern Univ.

Model reference adaptive control of flexible robots in the presence of sudden load changes, H. Kaufman, G. Neat, Rensselaer Polytechnic Institute . . . . [1387-14]

Adaptive gross motion control: a case study, M. B. Leahy, Jr., P. Whalen, G. B. Lamont, Air Force Institute of Technology . . . . [1387-15]

Minimum jerk trajectory planning for robotics, K. Kyriakopoulos, G. N. Saridis, Rensselaer Polytechnic Institute . . . . [1387-16]

Stability regions for the PUMA-569 Under Model, K. P. Valavanis, Northeastern Univ. . . . . [1387-17]

Intelligent grasp control, H. E. Stephanou, George Mason Univ. . . . . [1387-18]